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ORGANIC PRODUCTION POTENTIAL OF ARTIFICIAL UPWELLING MARINE CULTURE

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Résumé: L'augmentation de la population mondiale et ses exigences croissantes présente des difficultés pour satisfaire ses besoins alimentaires et énergétiques. Les réserves restreintes de pétrole et de terres arables limitent l'expansion possible de l'agriculture et de l'élevage.

Les eaux de surface des océans tropicaux constituent le plus grand réservoir d'énergie solaire du monde. La température de l'eau à moins de mille mètres en dessous de cette surface chaude est d'environ 5°C. Ces eaux de profondeur constituent une immense source froide et il est possible d'extraire de l'énergie méchanique en insérant un engin thermique entre les eaux chaudes et froides. L'énergie nécessaire pour pomper l'eau profonde à la surface représente à peu près 6.5% de l'énergie produite par l'installation.

Sa teneur en nitrate, en phosphate et en d'autres éléments rend l'eau profonde un excellent milieu de culture pour le phytoplancton quand elle est exposée à la lumière en surface.

L'extrapolation de résultats d'essais à petite échelle, obtenus à notre station de "Résurgence Artificielle" de St. Croix (Iles Virginies, Etats Unis d'Amérique), indique que ce système de mariculture à base d'eau profonde pourrait produire vingt fois plus de protéines d'algues par hectare que la luzerne, qui produit plus de protéines par unité de surface que n'importe quelle autre plante en agriculture intensive. Plus que 30% de la protéine d'algues, ainsi produite, est convertie en

protéine de palourdes.

Basé sur ces resultats, nous recommendons un essai commercial de ce système de mariculture, en utilisant l'effluent d'un système exploitant l'énergie thermique des mers.

Abstract: Increased population and rising expectations have put an enormous strain on the world's energy and food supplies. Petroleum reserves and land-resource limitations severely limit the expansion of conventional agriculture and animal husbandry.

In tropical and subtropical areas of the oceans, the warm surface waters constitute the world's largest storage of solar energy. The underlying cold deep water, less than 1,000 meters below the ocean's surface, constitutes a cold sink, making it possible to generate mechanical energy by inserting a suitable heat engine between the warm and cold waters. The energy required for pumping the deep water to the surface is typically 6.5% of the total energy produced by the plant.

The nitrate, phosphate and other nutrients dissolved in the deep sea water constitute the raw materials for plant growth when brought into the light at the surface. Extrapolation of results from small-scale experiments conducted at the St. Croix (United States Virgin Islands) "Artificial Upwelling" station, indicate that this system could produce twenty times more algal protein per hectare than alfalfa, the highest protein-producer per hectare in land-based agriculture. The algal protein can be converted into clam protein with better than 30% efficiency.

It is recommended that a commercial feasibility test of a combined sea-thermal power plant and mariculture operation utilizing deep-sea water and sunshine as major raw materials be undertaken.

Introduction: Increased population and rising expectations have put an enormous strain on the world's energy and food supplies. Humanity is expected to increase from the present four billion to between six and seven billion by the year 2000. Already now, five hundred million people are suffering from protein-deficiency. Pimentel and his collaborators (1975) have demonstrated that both petroleum and land-resource limitations make it impossible to feed the present population a United States diet (in which 69% of the total protein intake is of animal origin) based on United States agricultural technology.

Very high levels of agricultural productivity requiring few man-hours have been achieved in highly developed nations through the intensive use of petroleum-dependent machinery and fertilizers. Pimentel *et al.* (1975) have estimated that even without an increase in world population, the world-wide use of these techniques would exhaust presently known petroleum reserves in 13 years. Another factor limiting the expansion of agricultural production is the availability of arable land. Most of the available land is in use, and although the arable land area can be increased through irrigation, this is a capital and energy-intensive practice. Because of these pressures on arable land and petroleum reserves, it is imperative that we explore alternative methods for protein production.

The constraint on arable land naturally points to the vast area of the oceans—particularly in the tropical and subtropical latitudes—as the world's largest collector and storage of solar energy.

However, the animal protein production derived from the sea is disappointingly small. The sea presently accounts for only 5-10% of world protein consumed. The world fish catch has apparently stabilized at 1970 levels (Mayer, 1976) and overfishing of many species has already occurred (e.g., sardines, whales, herring). The total fish production in the oceans, which is obviously closely related to total biomass production, varies greatly with the different oceanic areas: thus, the "open ocean" with 90% of the surface area of the world's oceans produces 0.7% of its fish, the coastal zones with 9.9% of the area produce 54% of the fish and the upwelling regions with only 0.1% of the surface area of the world's oceans produce 44% of the fish (Crisp, 1975).

This natural phenomenon of high biological productivity in upwelling areas has stimulated our research in "Artificial Upwelling." "Artificial Upwelling" utilizes sunshine and deep-ocean water as raw materials to produce energy and high-quality protein.

Its protein production potential per unit area exceeds that of most agricultural systems, and it is not dependent on petroleum for fertilizer and energy.

"Artificial Upwelling" derives mechanical energy from the temperature differential between the warm surface water and the cold deep water in the tropical and subtropical oceans. Only a small proportion of the total energy generated is required to drive the pumps to bring the deep water to the surface. The deep water is also rich in nutrients (nitrate, phosphate, etc.) compared to surface water. These nutrients can be used as fertilizer to produce plant biomass for marine food chains. In a small land-based pilot plant on the North Shore of St. Croix (U.S. Virgin Islands), the authors have demonstrated the technical feasibility of the biomass production based on deep-sea water and numerous paper studies have analyzed the engineering and economic feasibility of power generation from the sea's temperature differential.

The Energy Resource: The ocean's waters are horizontally stratified and the deep-ocean water is uniformly cold. In tropical areas the temperature differential between the sun-warmed surface layer and the deep cold water is 20°C; this differential varies but little throughout the year. This temperature difference can be utilized to create mechanical energy by inserting a suitable heat engine between the warm and cold layers; such an engine would have a low Carnot efficiency because of the small temperature difference, but the resource is practically inexhaustible and renewable because it is powered by the sun. As demands for fossil fuels increase and they become more difficult to mine, the net energy gains (gross energy less the energy cost of extraction and delivery) resulting from their recovery decreases: we have seen examples of this in the current expensive exploitation of Alaskan and North Sea oil.

The concept of utilizing this temperature differential to run a heat engine is credited to d'Arsonval (1881). Claude (1930) constructed and operated such a plant on the North Shore of Cuba; the plant's operation was short-lived because of trouble with the cold-water pipeline, but he did demonstrate that the process was technically feasible. Since that time, numerous paper studies (Anderson and Anderson, 1966; Lockheed, 1975; TRW, 1975) have demonstrated that such a plant could be constructed utilizing present-day technology. There are wide variations in the projections of the cost of the power produced by such "sea-thermal power plants." These plants could use the "open" or Claude-cycle process, in which the warm water is evaporated under low pressure to drive a turbine, or the "closed" cycle process, in which an intermediary fluid such as ammonia, freon or propane, is evaporated by the warm surface water and condensed by the cold deep water. The "closed" cycle is advantageous because the working pressures are greater and therefore allow for conventional turbine design. However, this system requires very large and expensive heat-exchangers between the working fluid and the warm and cold water. The "open" cycle avoids this problem, but requires a large turbine capable of efficient work at low pressures, and may involve problems with dissolved gases in sea water. Other problems with ocean-thermal energy conversion (OTEC) plants include corrosion and biofouling, but the general consensus is that the difficulties can be solved.

The energy available from the resource is best expressed in terms of cubic meters of deep water, since long and large-diameter pipelines must be used to obtain the deep water, and because pumping costs must be considered. For a cold source at 280°K and a warm source at 300°K, the maximum theoretical efficiency for full utilization of the resource (Van Hemelryck, 1975) is:

$$\eta_{max} = \frac{1}{2}\left(\frac{300}{280} - 1\right) = .0357$$

and the maximum available energy is:

$$W_{max}/m^3 = k\Delta\eta_{max} = 2.91 \times 10^6 \text{ J/m}^3$$

where k = specific heat of water = 4.187×10^6 J/(°K m^3)

Van Hemelryck (1975) has discussed a Rankine-cycle plant which makes optimal use of this resource. At the limit for an optimal plant, the discharge temperature of the cold water (T'_c), and that of the warm water (T'_h), should be equal ($T'_c = T'_h$). Further, assuming a three-stage (multiple evaporation) plant and a surface water:deep water ratio of 3:1, he has shown that with a ΔT of 20°K the theoretical output would be 1.642×10^6 J/m^3, neglecting irreversible losses associated with the operating equipment. Because net yield will depend upon various economic factors and the actual design of turbines, pumps, and (for the "closed" cycle) heat-exchangers, a precise estimate of usable energy from this process cannot be made. For a proposed "open"-cycle plant at Abidjan, Ivory Coast, Salle and Capestan (1957) estimated a gross energy production of about 1.0×10^6 J/m^3 of deep water. A 100 MW plant would thus require approximately 3.15×10^9 m^3/yr. In contrast, a recent "closed"-cycle design commissioned by the U.S. Energy Research and Development Administration (Lockheed, 1975) would require pumping almost 18 times the volume of deep water, 5.7×10^{10} m^3/yr, to achieve a gross output of 250 MW. Anderson and Anderson (1965, 1966) estimated that, for a 33 MW plant producing 302 kW/m^3/sec the pumping costs would require 6.5% of the gross power production. For a plant of this size, pumping costs would therefore be 1.96×10^4 J/m^3. This cost would undoubtedly go down for larger plants.

The Organic Production Potential in Artificial Upwelling Marine Culture: After its utilization in the condenser of a sea-thermal power generating plant, the deep water is unaltered except for its temperature, and can be utilized as a source of nutrients for mariculture.

The technical feasibility of "Artificial Upwelling" mariculture has been demonstrated in a small plant on the North Shore of St. Croix, U.S. Virgin Islands (17°47'N, 64°48'W) in the Caribbean Sea. The site on St. Croix was chosen because the ocean reaches a depth there of 850 m, approximately 1.6 km offshore. Three polyethylene pipelines, each 1830 m long and 7.5 cm in diameter, were installed from shore into the sea to a depth of 870 m. The pipelines were installed in 1972 and have brought deep water to shore continuously since that time; the present deep-water flow is 250 liters/min. As shown in Figure 1, the deep water is pumped into two 45,000-liter (12,000 gallon) pools. Diatoms grown in these pools are started from laboratory cultures, then cultured in 757-liter (200-gallon) tanks which are used to inoculate the pools. One diatom, *Chaetoceros curvisetus* Cleve (STX-167) can be grown in continuous culture in unsupplemented deep water, frequently for up to 40 days, at a turnover rate of one pool volume per day. The pool cultures are pumped continuously into shellfish tanks at metered rates, depending upon the feeding activity of the shellfish: an algal stripping rate of about 90% is maintained. The system also contains a hatchery, where the clam *Tapes japonica* (Deshayes) is regularly produced, a larvae-setting area for juveniles, an experimental shellfish area used to determine optimum feeding ratios, animal density, etc., and a pilot shellfish-rearing area used to test results of small-scale studies and for preliminary economic determinations. Food to these areas can be supplied from the pools or from a wide range of algae grown in elevated 2000-liter culturing vessels ("reactors"). In addition, a separate set of ten 2000-liter reactors is used to study the possibility of maintaining continuous cultures using a surface-water inoculum.

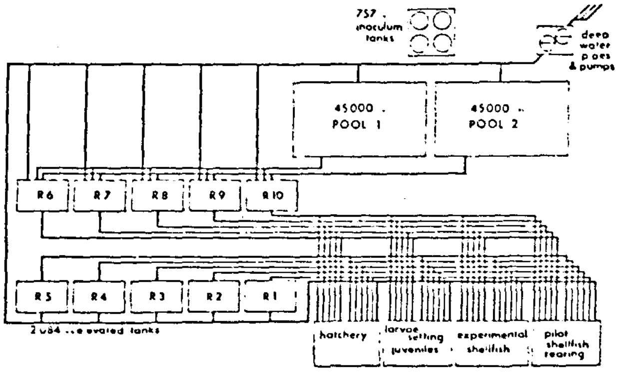

Figure 1. Outline of the experimental deep-sea water mariculture facility on the North Shore of St. Croix, U.S. Virgin Islands.

Table 1 gives the concentration of the major nutrients necessary for algal growth in deep and surface water at St. Croix.

Table I. Nutrient Concentration in the Deep (870-m) and Surface Waters North of St. Croix, U.S. Virgin Islands

	Nutrients (µg-at/liter)				
	(NO_3+NO_2)-N	NO_2-N	NH_3-N	PO_4-P	SiO_4-Si
Surface Water (3 km offshore)	.2	.2	.9	.2	4.9
870-m Deep Water	31.3	.2	.7	2.1	20.6

The yearly temperature range in the shellfish tanks is 22-29°C. Ten species of shellfish have been screened for growth and survival in the

St. Croix system. Eight species grew well and reached market size quickly. They are the European oyster (*Ostrea edulis*), the Pacific oyster (*Crassostrea gigas*), the Pacific oyster for the half-shell trade (*C. gigas*, Kumomoto variety), the Japanese little-neck clam (*Tapes japonica*), the Southern clam or quahog (*Mercenaria campechiensis*), F_1 clam (a cross *M. campechiensis* X *M. mercenaria*), the bay scallop (*Argopecten irradians*), and the Japanese pearl oyster (*Pinctada martensii*).

The Japanese little-neck clam reproduced in the system and a third generation has been produced.

Spiny lobsters, Queen conch and carrageenan-producing seaweeds are grown in the effluent of the shellfish tanks. Studies to test the feasibility of rearing the Queen conch (*Strombus gigas*) on algae growing on the sides and bottoms of ponds are underway. The spiny lobster, *Panulirus argus*, is being reared on culled shellfish. *Hypnea musciformis*, a carrageenan-producing red seaweed, doubles its weight every three days by stripping ammonia (an animal excretory product) from the shellfish tank effluent.

Primary production: One of our main goals at St. Croix is maximal algal productivity. Since inorganic nitrogen (nitrate, nitrite and ammonia) is the limiting nutrient for algal growth in deep-sea water, we have expressed our algal production in terms of protein per hectare, based on the efficiency of inorganic-nitrogen to algal-protein conversion. The latter is dependent upon internal (or species-specific) variables as well as upon external variables such as temperature, nutrient concentration, dilution rate, and pool depth.

In the pools at St. Croix, *Chaetoceros curvisetus* regularly attains a concentration of 25 µg-at of protein-nitrogen/liter. Since the inorganic nitrogen concentration in the incoming deep-sea water is 32 µg-at per liter, this represents a conversion of deep water dissolved inorganic nitrogen to phytoplankton protein-nitrogen of over 78%. Assuming only 70% efficiency of inorganic nitrogen to protein-nitrogen conversion, at one turnover per day, and with a pool depth of 1.0 m, the protein production/m^2/yr in the St. Croix experimental system for 330 days operation of the pools per year (35 days down-time for cleaning and restarting of the pools) would be:

$$\frac{32}{10^3} \times 14 \times \frac{70}{100} \times 6.25 \times 800 \times 330 = 0.52 \text{ kg}$$

or 5.2 tons protein/hectare/year.

To maximize the phytoplankton-protein which can be produced per unit surface area and per m^3 of deep water, the optimal pool depth and turnover (dilution) rate of the pools should be determined.

Farmer (M.W. Farmer, 1976, Doctoral dissertation, Biology Department of The City College, New York; in preparation) studied productivity of *Chaetoceros curvisetus* (STX-167) in outdoor cultures in 80-cm deep, 2000-liter vessels as a function of the culture turnover rate and light intensity. Light intensity was controlled through the use of neutral density screens which regulated the surface light intensity of the cultures at 3%, 20%, 30%, 46%, or 100% of the natural sunlight intensity (I_O) on the beach in St. Croix. Light attenuation in each culture was determined at sunset and sunrise each day by measuring subsurface and bottom light intensities. Four different deep-water flow rates were used for each light condition: .25; .70, .95 and 1.20 turnovers/day. For simplicity, we discuss below the results of those cultures in which the surface light intensity was $0.3 \times I_O$ only; or $\alpha = 0.3$. From these data, pool depth, light attenuation, turnover rates, and hence productivity values, for an optimized algal system were constructed. It must be emphasized that an "optimum" set of algal pool parameters (depth vs length and width) must take into account economic factors such as cost of excavation, maintenance, etc., and therefore that depth which provides the maximum production per unit surface area may not be the best in terms of capital or maintenance costs. For this reason, we have chosen to base our productivity estimates upon what at present appears to provide the optimum cost/productivity ratio in addition to those estimates providing greatest absolute productivity.

To determine the optimized productivity estimates, differences between the light intensity at the top and bottom of the reactors at different dilution rates were used to calculate the light attenuation coefficient, k. From these absorbance values, a least-squares parabola regression was constructed to extrapolate to other dilution rates. This parabola is shown in Figure 2. The peak absorbance value is obtained for .81 turnover/day, under these experimental conditions. Next, the corresponding pool depths were calculated. The depth for a pool with 100% incident light was defined as that depth at which the average light intensity (I_{av}) in the culture is the same as the average light intensity in the screened experiment at the same turnover rate. Pool depths were calculated by first defining the average light for each culture according to the expression:

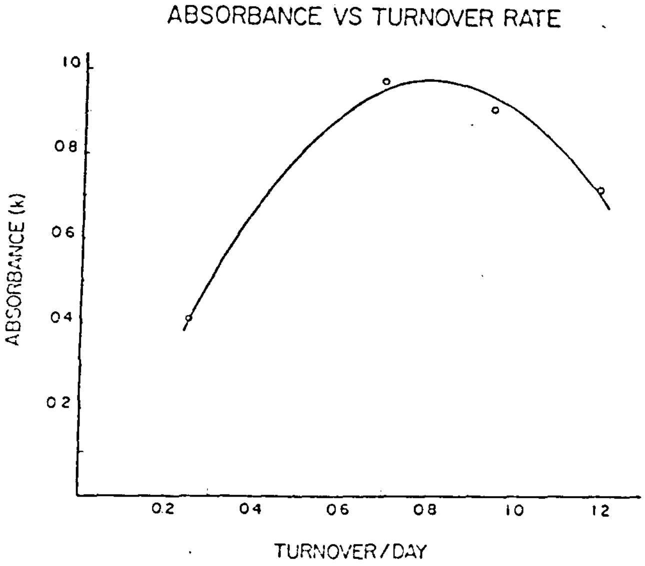

Figure 2. Absorbance vs turnover rate.

$$I_{av} = \alpha I_o \left(\frac{1-e^{-kz}}{kz}\right)$$

where α = proportion of incident light penetrating a neutral density screen and striking the surface of the culture;

I_o = illumination immediately below the surface in the absence of a screen;

z = depth.

For the selected data, obtained for $\alpha = 0.30$, I_{av} was very close to the theoretical 0.215 I_o average light for a 100% incident light culture with depth equal to the compensation depth. The compensation depth is the depth at which energy lost through respiration is equal to energy gained through photosynthesis. Light attenuation at that depth is 0.01.

In a second step, the depth of cultures with the same absorbtivity (k), for each turnover rate, which would also "see" the same average illumination, when subjected to unattenuated ($\alpha=1.0$) sunlight, was determined. Figure 3 illustrates the relationship between turnover rate and equivalent depth.

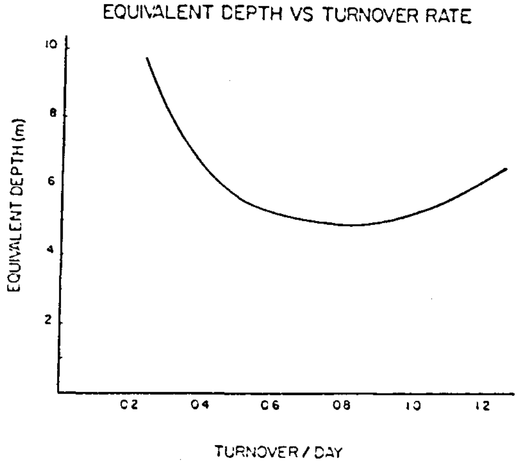

Figure 3. Equivalent depth vs turnover rate.

In these studies, direct measurements were made of cell density and particulate nitrogen: 10^8 cells contained 0.388 mg particulate nitrogen. From these data protein concentration vs turnover rate could be estimated: the relationship is illustrated in Figure 4. Protein concentration decreases with increasing turnover rate.

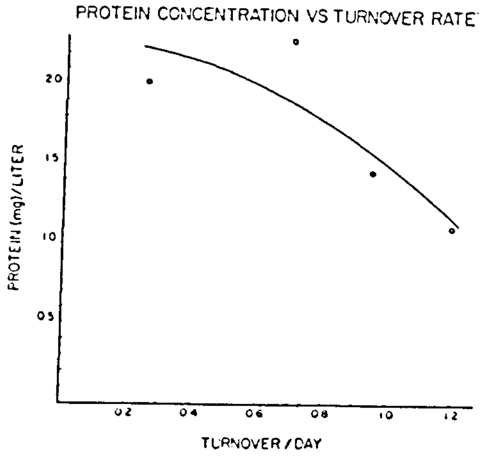

Figure 4. Protein/liter vs turnover rate.

Figure 5 illustrates the relationship between the volume of deep-sea water (m^3) handled per m^2/day and the protein produced in g/day. Since they are not linearly related there will undoubtedly be a trade-off between increased productivity, the cost of constructing a deep pool, and the cost of pumping large volumes of water.

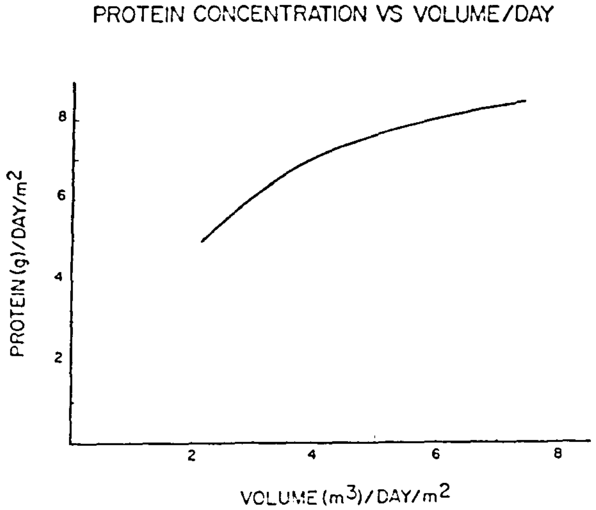

Figure 5. Protein vs volume.

Table 2 summarizes the data discussed above. Tentatively, we chose our "optimum" pool depth as 4.87 m; this represents peak light attenuation and a good compromise between depth and productivity (6.99 grams protein/m^2/day). The maximum productivity within the explored range is obtained with a 6.10-m pool depth at a turnover rate of 1.2/day and yields 8.42 grams protein/m^2/day. These extrapolations are based on many assumptions and have to be verified experimentally.

Table II. Turnover Rates, Attenuation Coefficient (k), Average Light Intensity, Depth, Volume Pumped per Unit Surface Area per Day, Cell Density and Cell Production, and Protein Production Values Based on Data Collected on a 0.8-m Deep Culture, with α=0.3

Turnover/ Day	k	I_{av}	Depth (m)	Volume/Day /m^2 (m^3)	Cells/ Liter (x 10^7)	Cells/ Day/m^2 (x 10^{10})	Protein/m^2/ Day (g)
.25	.4110	.2557	9.30	2.325	9.20	21.4412	5.20
.50	.8021	.2214	5.57	2.785	8.60	23.9844	5.81
.70	.9533	.2099	4.95	3.465	7.80	27.1344	6.58
.81	.9754	.2083	4.88	3.953	7.30	28.8159	6.99
.95	.9408	.2108	5.00	4.750	6.45	30.8180	7.48
1.00	.9114	.2130	5.10	5.10	6.20	31.4721	7.63
1.20	.7044	.2293	6.11	7.332	4.75	34.7463	8.42

The energy cost of producing phytoplankton protein is another important consideration. As indicated earlier, the deep-water pumping costs are typically 1.96 x 10^4 J/m^3. For a plant of given size this is a constant, but the costs per hectare of ocean or land surface, and therefore the energy input vs food energy output ratios for a given surface area, will depend upon the depth and turnover rates of the pools.

Table 3 illustrates these relationships for the deep-water effluent from the condenser of a hypothetical 100 MW OTEC plant. Clearly, the area required decreases with increasing pool depth and turnover rate. On the other hand, the cost of energy per hectare and hence the ratio of the energy input/food energy output increases. Perhaps the most relevant way of judging the importance of these figures is to compare the potential productivity of an "Artificial Upwelling" system to various terrestrial crops.

Table III. Hectares Required for Full Utilization of 100 MW OTEC Plant Deep-Water Discharge, Pumping Energy Required, Food Energy Produced, and Energy Input/Output Ratio for Pools Varying in Depth and Turnover Rate

Turnover/ Day	Depth (m)	Hectares Required*	Pumping Energy Required (kg-cal/ha/day) ($\times 10^5$)**	Food Energy Produced (kg-cal/ha/day) ($\times 10^5$)***	Energy Input/ Energy Output
.25	9.30	2787	1.09	4.48	.24
.50	5.57	2328	1.30	5.01	.26
.70	4.95	1870	1.62	5.67	.29
.81	4.88	1639	1.85	6.02	.31
.95	5.00	1364	2.22	6.44	.34
1.00	5.10	1270	2.39	6.58	.36
1.20	6.11	883	3.44	7.25	.47

*Lockheed Design (1975) = 6.48×10^7 m^3/day.

**Deep-water pumping costs = 1.96×10^4 J/m^3. 10^5 kg-cal=4.185×10^8 J.

***Algal protein = .58 ash-free dry wt. 1.0 g ash-free dry wt=5 kg-cal.

Table 4 illustrates the primary (algal) productivity which could be obtained with a deep-sea water mariculture system with the primary productivity of selected land products. These products which provide the best protein output (alfalfa), highest output in terms of weight (corn silage) and require the lowest fuel energy input (cassava) were chosen for comparison. All comparative data are from Pimentel et al. (1975). The "minimum" figures assume a 9.3-m deep pool with a .25/day turnover rate. "Optimum" and maximum figures assume a 4.87 or 6.1-m deep pool

Table IV. Primary Production per Hectare per Year for Chosen Terrestrial Crops and for Phytoplankton Grown in 100% Deep Water. For "Artificial Upwelling", 1 Year = 330 Days' Production

Type of Crop	Crop Yield in Protein (kg)	Crop Yield (kg)	Crop Yield Food Energy ($\times 10^6$ kg-cal)	Energy Input** ($\times 10^6$ kg-cal)	Energy Input/ Energy Output	Energy Input (kg-cal)/ Protein Output (grams)
Terrestrial*						
A) Alfalfa (highest protein production)	710	6,451†	11.4	2.694	.24	3.79
B) Corn Silage (highest crop yield in weight)	393	30,200	24.1	5.493	.23	13.97
C) Cassava (lowest fossil energy input)	58	5,824†	19.2	0.016	.0008	.27
Marine (Artificial Upwelling; Phytoplankton)						
Minimum***	17,160	28,586†	147.9	35.93	.24	2.10
"Optimum"***	23,063	39,764†	198.8	61.10	.31	2.65
Maximum***	27,793	47,719†	239.6	113.32	.47	4.08

Footnotes to Table IV:

*Comparative data are from Pimentel et al. (1975).

**Energy input = fossil-fuel energy for terrestrial sources and deep-water pumping costs for "Artificial Upwelling".

***See text for explanation of terms.

†Dry weight (kg).

with turnover rates of .81 and 1.2/day, respectively. In terms of its production of protein, dry weight of crop and food energy, the mariculture system compares very favorably. The energy input required for each hectare/year is, of course, greater than for the terrestrial products, but for the terrestrial products this is fossil-fuel energy which we again stress is becoming increasingly scarce and expensive. In terms of energy input vs food energy output, the various systems are very close, except for cassava. The reason for this is that labor is substituted for fossil-fuel-derived energy. Pimentel et al. (1975) estimate that in excess of 1,200 man-hours/year are required for each hectare of cassava production; this compares with about 25 man-hours for corn silage. Labor costs are an important element of comparative data, but they are not yet available for the mariculture system. Considering that a source of energy will be easily available from the OTEC facility, mariculture is likely to be a highly mechanized, energy-intensive business with low man-hour requirements. Our calculations do not include energy costs other than the costs of pumping the deep-ocean water. In any case, it will be noticed that in terms of kg-cal input vs protein output, the mariculture system compares very favorably with corn silage and encompasses the figure for alfalfa.

Secondary production: The algae produced in the St. Croix "Artificial Upwelling" system have been used as food for filter-feeding shellfish: clams, oysters and scallops. The conversion of deep-sea water nitrate to algal protein and further to clam-meat protein was studied at the St. Croix Station. A mixture of unialgal cultures of *Chaetoceros curvisetus* (STX-167) and S-1 (an unidentified naked flagellate) was used. The cultures were grown individually and continuously in onshore pools, combined in a mixing tank and fed continuously to several batches of *Tapes japonica* for 36 days. The clams in each batch were culled every 9 days to bring them back to the original weights. Thirty-five, 70 and 140-gram batches of clams in a 4-liter container received a continuous food flow-rate of 1.0 ml/sec. Thirty-five, 50, 70, 100, and 140-g batches of clams in 4-liter containers received a 2.0 ml/sec food flow rate. The particulate protein and dissolved NH_4^+, NO_3^- plus NO_2^-, entering and leaving each shellfish tank were measured daily. Every 9 days, all the clams were weighed and measured; enough clams were harvested to bring the total population weight back to its starting level, and the tank deposit was determined for each group. Sixty-nine percent of the 31 μg-at/liter nitrate-nitrogen in the deep water was converted into algal protein nitrogen over the 36-day period. From 31% to 35% of the algal protein entering the *Tapes* feeding tanks was converted into clam-meat protein by the 1 ml/sec flow groups and between 24% and 33% of the algal protein was converted into clam-meat protein by the 2 ml/sec flow groups. The fastest individual clam growth was obtained in the 35-g, 2 ml/sec group, with a 1.42 mm/week shell-length increase and a .411 g/week/g whole clam weight increase. The greatest clam population growth occurred for the 100-g, 2 ml/sec group with a total weight gain of 134 g in 36 days.

The fastest individual clam growth was obtained at the lowest percent stripping of algal protein nitrogen. Ammonium ion concentration in the shellfish tank was highest at the slowest individual clam growth rate. The Protein Efficiency Ratios in this experiment varied between

8 and 14, indicating that the algal food source is a good one for Tapes japonica. (Roels et al., 1977. To be presented at World Mariculture Soc. Mtg., January 9-12, Costa Rica.) These results are summarized in Figure 6.

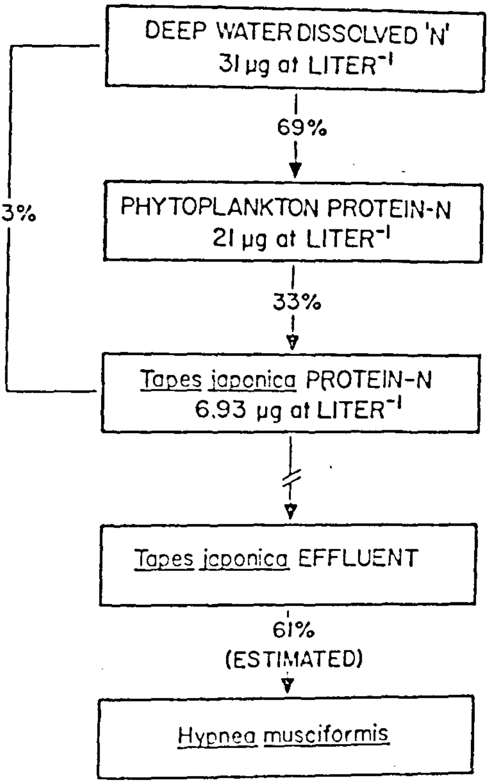

Figure 6. A summary of a recent (December 1975) food conversion study carried out at the "Artificial Upwelling" site at St. Croix. Total conversion efficiency for deep-water nutrients to Tapes japonica meat protein was 23%, considerably higher than achieved in conventional agriculture and animal husbandry. The red seaweed Hypnea musciformis has been grown in the Tapes tank effluent with a 61% efficiency of conversion of the ammonia in this tank effluent.

We have also grown the carrageenan-containing seaweed in the Tapes tank effluent. In the experiment described above, this effluent contained about 2 µg-at NH_3-N per liter, and preliminary studies indicate that about 61% of this available nitrogen can be incorporated by Hypnea. The use of another such primary producer could further benefit the overall biological and economic productivity of deep-sea water OTEC plants and mariculture systems.

Comparison between "Artificial Upwelling" marine culture and agriculture and animal husbandry: Table 5 compares the protein conversion efficiency obtained in "Artificial Upwelling" mariculture experiments with those of various other secondary producers. In small-scale experiments, the St. Croix mariculture system achieved a better plant to animal protein conversion than is achieved in cow's milk production, which is the most efficient animal protein production system known in conventional agriculture and animal husbandry.

In recent studies, surface water was used as an inoculum for deep water and the resultant phytoplankton was fed to the clam Tapes japonica (S. Laurence and O.A. Roels, 1976, "Plant and animal protein production in a mariculture system utilizing deep (870-m) and surface water mixtures," in preparation). Such inoculations would be economically

Table V. A Comparison of the Plant-to-Animal Protein Conversion Efficiency Obtained in the "Artificial Upwelling" System with Other Efficient Secondary Producers

Animal Product	Animal Protein Output / Vegetable Protein Input
Milk*	31.4
Eggs*	27.1
Beef (feedlot)*	6.5
Catfish*	10.5
Shellfish (*Tapes japonica*)**	33.0

*The comparative data for these products are from Pimentel *et al.* (1975).

**Shellfish data from the St. Croix "Artificial Upwelling" mariculture system.

advantageous since the system would not require extensive laboratory culturing facilities. A mixture of 80% deep and 20% surface water was used. Cultures obtained peak density within five days and were usually dominated by *Chaetoceros curvisetus*. These cultures were maintained for up to 40 days at 1 turnover/day on a 2,000-liter scale. Shellfish fed phytoplankton grown under these conditions converted the plant protein into animal protein with an efficiency of 35%. The results are summarized in Figure 7.

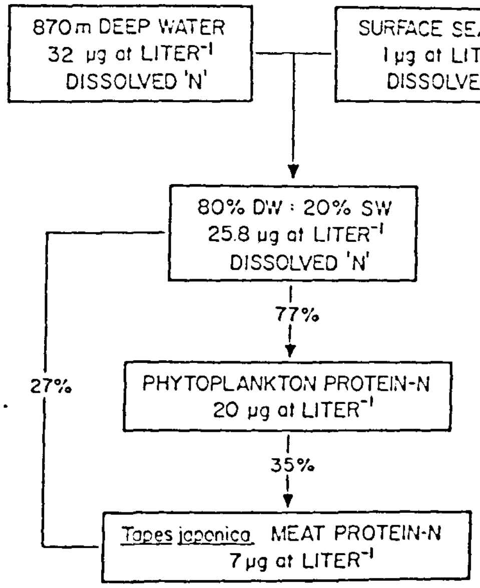

Figure 7. Summary of a food conversion study using surface water to inoculate deep water. Cultures were dominated by the diatom *Chaetoceros curvisetus* and were maintained at one turnover per day for up to 40 days with a constant ratio of 80% deep and 20% surface water.

Conclusion: Available experimental evidence indicates that "Artificial Upwelling" marine culture can produce substantial quantities of high-quality plant and animal protein. While conventional agriculture and animal husbandry are faced with increasing cost and scarcity of arable land and petroleum, "Artificial Upwelling" could generate more electrical power than the food production requires and would not utilize artificial fertilizers.

In view of the present population pressure on food, energy, water and land resources, the outlook for improving humankind's lot is grim.

If successful, "Artificial Upwelling" would generate power from the sun and could produce high-quality animal protein in large quantities. Its commercial feasibility should be tested now.

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