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THE FUTURE OF MARINE AQUACULTURE IN ENERGY SYSTEMS

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WORLD FOOD NEEDS AND PRESENT RESOURCES

Conservative estimates of the world's human population 30 years from now range from 5.3 to 7.4 billion with 80 to 85% living in underdeveloped countries (Potter, 1969). This is about double the present population (3.5 billion). More people will require more arable land for food. At the same time, more room will be required for human habitation and for industry. Historically, competition for arable land has been keen as few people want to live and work on arid deserts, tundra, or rugged mountains.

It is conceivable that an extension of normal agriculture will meet the world's food needs for a few more years provided that there are no natural disasters. But, as competition for arable land increases, there will be a greater need for food from the sea.

The self-sustaining resources of the sea, however, are limited. The current annual yield of fish and shellfish is about 58×10^6 tons. The earth's oceans cannot supply us with much more than 220×10^6 tons per year of wild stocks of fish and shellfish on a sustained yield basis. By comparison, the land is now producing 1650×10^6 tons of human food per year. Thus, present harvests of the sea represent only 3.5% of today's terrestrial production, and a maximum potential of only 13.3% of the present agricultural food resources (Webber, 1968). If 3.5 billion people use 1708×10^6 tons of food per year, then 30 years from now the world population will require some 3400×10^6 tons of food per year. This represents a projected deficit of 1320×10^6 tons of food per year in the year 2000, assuming that there are no substantial increases in terrestrial food production. Obviously, dramatic increases in food production will be necessary.

MEETING THE WORLD'S FOOD NEEDS

It would be far better politically and economically if the underdeveloped countries could meet their own food requirements (Pirie, 1967). Practically, this will be difficult until appropriate technology is available for specific area needs. Thus, for at least a decade, some agriculturally advanced countries will have to intensify their food production and surplus food will have to be sent to underdeveloped countries.

Future generations will have to become accustomed to getting proteins from many more sources. Engineers and biologists visualize food producing systems which use the waste thermal energy from electric power plants, the nutrient energy from domestic sewage (containing human waste primarily), and the organic byproducts of industry (Fig. 1). Hardin (1969) has even determined the relative caloric value of our petroleum reserves in terms of feeding people instead of consuming it as fuel for industry and engines. Even now, the French are not only producing but selling, protein produced by fermentation of low-grade petroleum (Potter, 1969). All of these innovative concepts of protein production will have to be developed by technologically advanced countries.

AQUACULTURE: FARMING THE THREE DIMENSIONS OF WATER

Fresh and saltwater fish, shellfish, and marine plants have been reared by man for centuries. Generally, intensive culture of shellfish and marine plants has required little or no supplemental feeding. Production has been increased primarily by mechanical innovations to intensify the use of the environment. An increase in fish production, however, is usually dependent on supplemental feeding (there are some notable exceptions, such as carp grown in rice fields). Unless the supplemental food of fish comes from unutilized sources, the intensive culture of fish does not add to the world food stores—it merely redistributes it, possibly with a net loss.

Domestic sewage represents a source of nutrient energy and waste. Cooling water (that is water pumped from thermal power plants) represents a source of mechanical and thermal energy. Biologists, and others, interested in intensive farming of marine organisms (mariculture) should be informed of the possible benefits of combining these forms of energy in a mixed energy system. Marine organisms can be grown in a controlled environment with thermal and nutrient wastes and can provide high-priced, quality products for luxury markets as well as low-cost, protein-rich products. For economic reasons, it will probably be necessary to intensify production of presently acceptable marine food organisms while developing markets for the new products. Establishing a new product is primarily a problem of social acceptance and cannot be taken lightly (Pirie, 1967).

POTENTIAL SOURCES OF THERMAL AND NUTRIENT WASTES FOR MARICULTURE

Concentrated sources of nutrient energy will come from urban wastes, carried along by fresh water. Some urban complexes, such as Seattle, Washington, have low ratios of industrial water use to human use. A metropolitan treatment plant in the Seattle area, designed for a population of 1.5 million, handles an average of 125 million gallons of water per day to dilute the human waste.

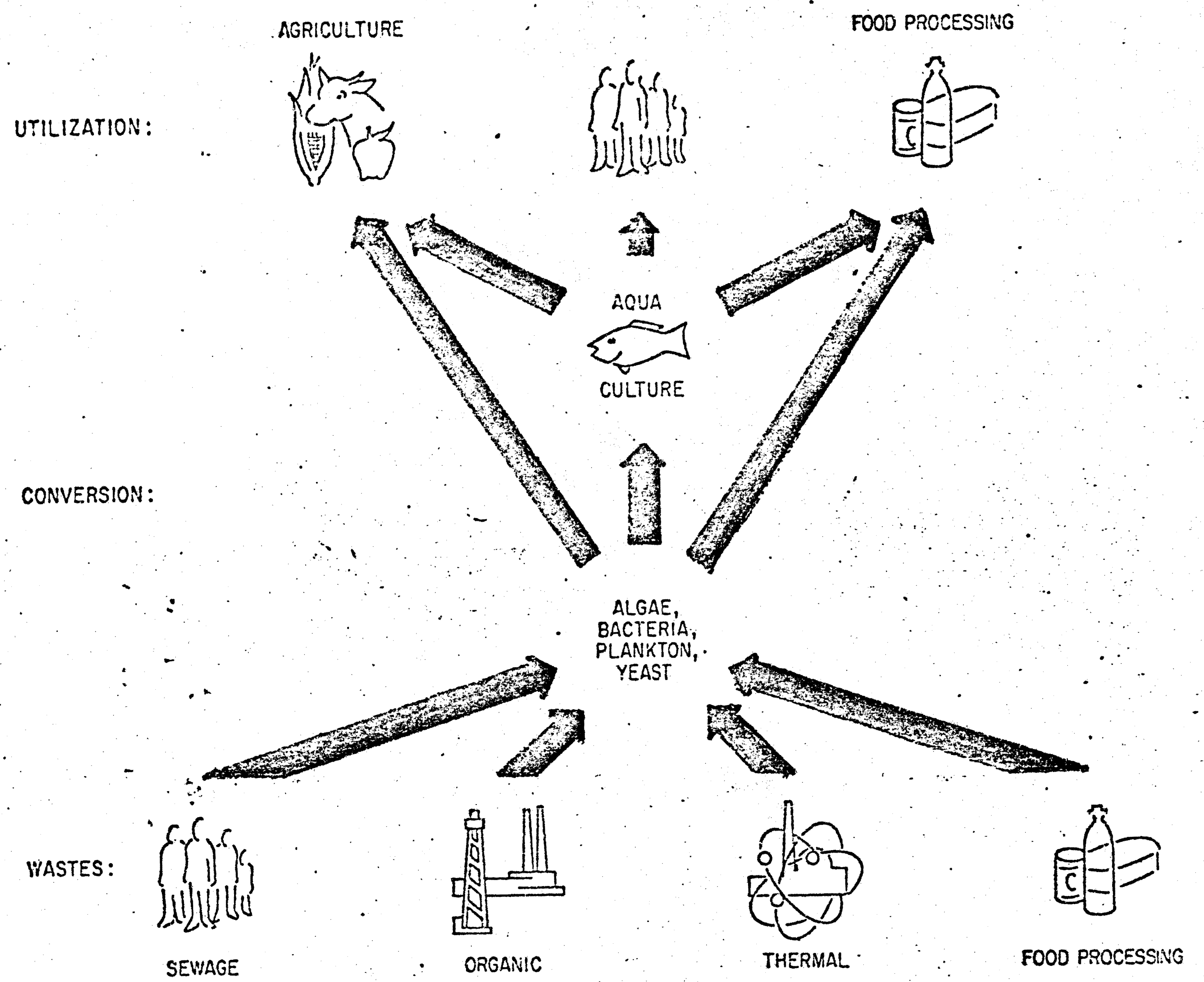

Figure 1. Maximum utilization of waste products for the production of food (From Potter - 1969)

A typical nuclear-fueled, saltwater-cooled power plant of 1,000-megawatt electric (MWe) capacity will use about 700,000 gallons of water per minute for cooling purposes and will raise the temperature of the cooling water by at least 10° C.

Three basic ways of using this waste energy are:

1. Nutrients from treated sewage can be mixed with salt water to feed algae cultured in large ponds. The phytoplankton may be used as feed for bivalve molluscs or other invertebrates, or for the production of protein and pharmaceuticals from sea weeds.

2. Discharges of thermal waste represent both caloric and mechanical energy because the water is heated and pumped. Systems using heated, flowing salt water can greatly increase the density and growth rate of cultures of finfish and invertebrates. Growing finfish at maximum capacity in such a system would require supplemental feeding. The capacity of a system for molluscan shellfish, however, would be dependent primarily upon the flow and the natural production of algae.

3. Waste nutrients and thermal discharges could be compatibly located for synchronous use. The design capabilities of such a duel system are technologically feasible for certain areas of the United States. Combining the discharges of a 125-million-gallon-per-day (m.g.p.d.) sewage treatment plant with that from a 1,000-MWe thermal plant would offer maximum ratios of 1 part nutrient-enriched water to 8 parts of warmed sea water, utilizing the full flow of both systems. Alternate discharge routes that bypass the maricultural facilities would provide an infinite variety of conditions tailored to suit the needs of mariculture.

UTILIZATION OF MIXED ENERGY SYSTEMS FOR MARICULTURE IN THE PACIFIC NORTHWEST

Many marine organisms in temperate waters that can be used for food are tolerant to wide ranges of temperature and salinity, a feature that is desirable for mariculture in mixed energy systems; most countries with highly-developed technology are within the temperate zones. For these reasons, the locations of most mariculture systems using byproduct nutrient and thermal energy from sewage treatment and power production will probably be in temperate zones for at least the next decade.

Figure 2 is a suggestion for such a system in the Pacific Northwest—the intensive culture of native fauna, supported by native flora. I am sure that eventually exotic fauna will play an important role in such systems.

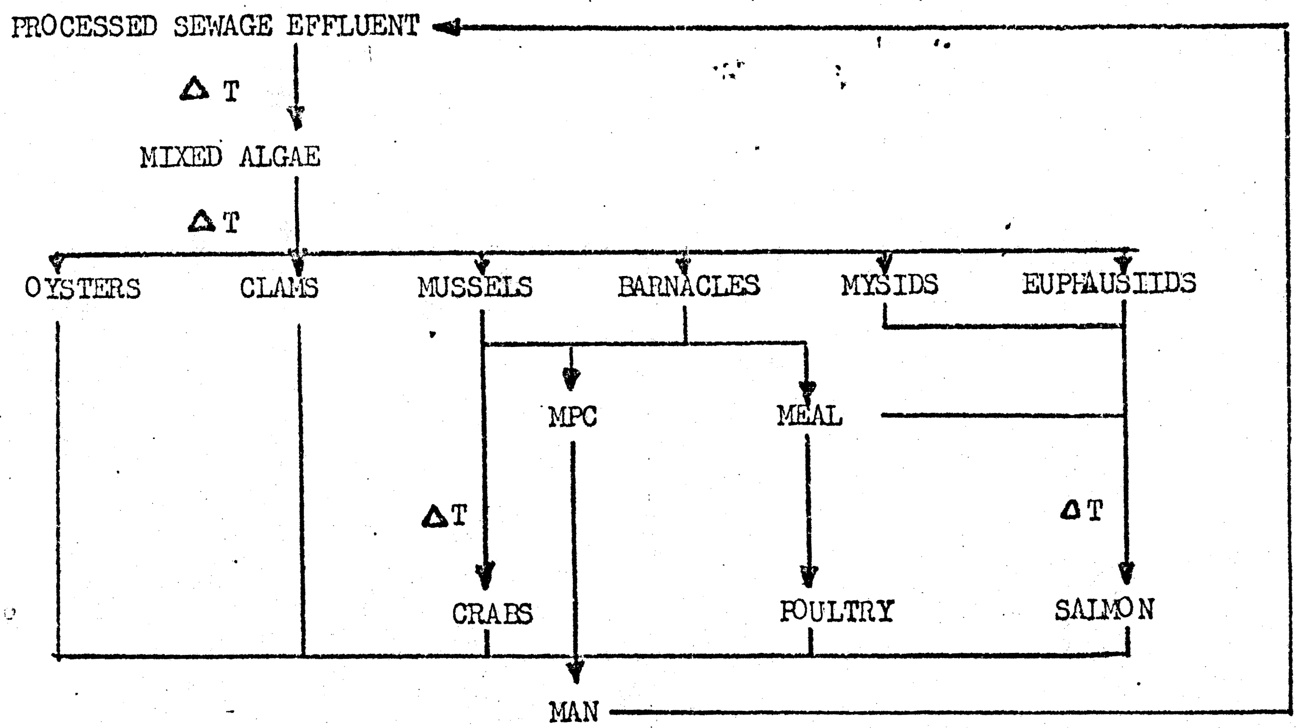

Figure 2. A possible use of processed wastes and thermal effluents for mariculture in the Pacific Northwest.

Native flora coming through the thermal plant will be fertilized by nutrients from effluent of sewage treatment plants. Potter (1969) reports that algae grown on sewage can produce an average of 40 tons of protein per acre per year. The crude protein yield of the algae is about 50%. Thus, a system using the sewage water alone should yield about 80 tons of algae/acre/year. Although algal culture in mixed effluent systems has been used experimentally for mariculture in England (Potter, 1969), production figures for large scale operations are not yet available. Golueke and Oswald (1965) were able to grow Chlorella at a density of 200 mg/liter in large ponds containing effluent from sewage treatment plants. At this density, a 2.5-acre pond 3-feet deep would have a standing crop of 20 tons of algae (about 8 tons/surface acre).

The rates of growth and dominance of mixed algae in such systems have been little studied, and the mariculture facility may require devices to control algae production. When we know what we need, however, engineers can probably design and build it. It is economically practical, for example, to remove nutrients from effluent that is excess to the maricultural system (Environmental Science and Technology, 1968b); we know that aeration in the ponds will probably be necessary (Environ. Sci. Technol., 1968c) (compressors can be run either from the electrical energy of the thermal plant, or from turbines powered by methane gas from the sludge digestors); and we know that iron and possibly other trace elements may have to be added to achieve maximum densities quickly (Leone, 1969). Ponds of varying algal densities linked in series may be required to provide the proper efficiency in nutrient assimilation (Gates and Borchardt, 1964). As algae cannot synthesize organic carbon, carbon dioxide may have to be forced through the ponds. Lastly, it may be necessary to provide underwater illumination at night and in the winter to maintain high growth rates.

Chlorination may be a serious problem in growing algae. For example, if our hypothetical plant with the 1:8 sewage to thermal waste ratio were to chlorinate the sewage effluent at 5 ppm Cl_2, the mixture at the thermal plant would contain 0.6 ppm chlorine (assuming no losses in transit). A continuous dose of 0.5 ppm Cl_2 in the condensors is sufficient to prevent fouling in a thermal plant and would probably be reduced to less than 0.1 ppm Cl_2 by the time it reached the fish growing ponds (Novotny).[1/] Plaice and lemon sole can be grown to market size under such conditions with no problems (Nash, 1968), but to my knowledge no information is available on the effects of chlorinated salt water in rearing salmonids. It is likely that production of shellfish and algae might be adversely affected in chlorinated salt water. I feel that the chlorination problem will be solved when the mariculturist can present the necessary facts to the engineer.

1/ Novotny, Anthony J. 1968. Problems of thermal effluents in marine and estuarine waters. Pacific Marine Fisheries Commission meetings. Coeur d'Alene, Idaho. 16 pps. 13 figs. (processed).

In the temperate zone, a maricultural system such as in Figure 2 should involve a variety of food and feed organisms. Monocultures are especially susceptible to blight. Mixed cultures should be less so, but the problem of disease needs further study. A better range of market products would be an obvious advantage of such a system.

The pilot plant depicted in Figure 3 is for a thermal energy system and would require ponding expansion for the addition of a nutrient system. In this system we visualize the production of seed oysters and mussels for transfer to large rafts in nearby growing areas. There is already a ready market for oysters and it should be possible to develop a market for fresh mussels. Other uses for mussels could be as sources of protein concentrate and as food for cultured fin fish. Nash (1968) found mussels to be an excellent food for plaice and lemon sole raised in tanks holding heated power-plant effluent.

As our knowledge of maricultural sanitation and nutrition increases, based on intensive research on feeds and feed sources from within and without the systems, the capacities of the mixed energy systems for growing finfish should increase dramatically.

For-example, Nash (1968) produced 0.4 lb/ft^2 of flatfish per year in the thermal discharge water from a power plant in Ayershire, Scotland. Bardach (1968) reports that the Japanese raised yellowtail fish (probably Seriola quinqueradiata) to harvest size by sequential cropping at a rate of 5.7 lbs/ft^2 per year. Jensen (1967) reports that 6.1 lbs/ft^2 of rainbow trout can be produced in saltwater ponds about 3 meters deep. The trout utilize the entire water column so that volume production is about 0.6 lbs/ft^3. This amount can be considered equivalent to annual production, as the trout can be easily harvested in a year's time (Fig. 4). If we assume that a mixed energy system should produce at least as much, one of the small ponds depicted in Figure 3 should produce 71 tons of trout per year.

Flow will be extremely important in the saltwater culture of salmonids. In a thermal or mixed energy system, we not only have high rates of flow, but the added advantage that the flowing water will be heated. The maximum utilization of this flow for the production of salmonids is depicted in Figure 5. In this case (a monoculture), the efficient utilization of the full flow from a 1,000-MWe (1,000 cfs) saltwater cooled thermal plant should produce at least 3,400 tons of trout per year, based on production figures from existing freshwater commercial trout farms. Such enormous production will require an enormous amount of feed. Research into the nutritional value and new sources of feed will be required.

The common bay mussel, Mytilus edulis, should be one of the prime organisms for study. In Spain, bay mussels are easily grown on long ropes hanging from rafts. Andreu (1968) reports that Spanish production reached 154,000 tons from 2,700 rafts in the bays of Galicia. Ryther and Bardach (1968) report that in one year, an 11 yard rope can produce 265 lbs of mussels, or about

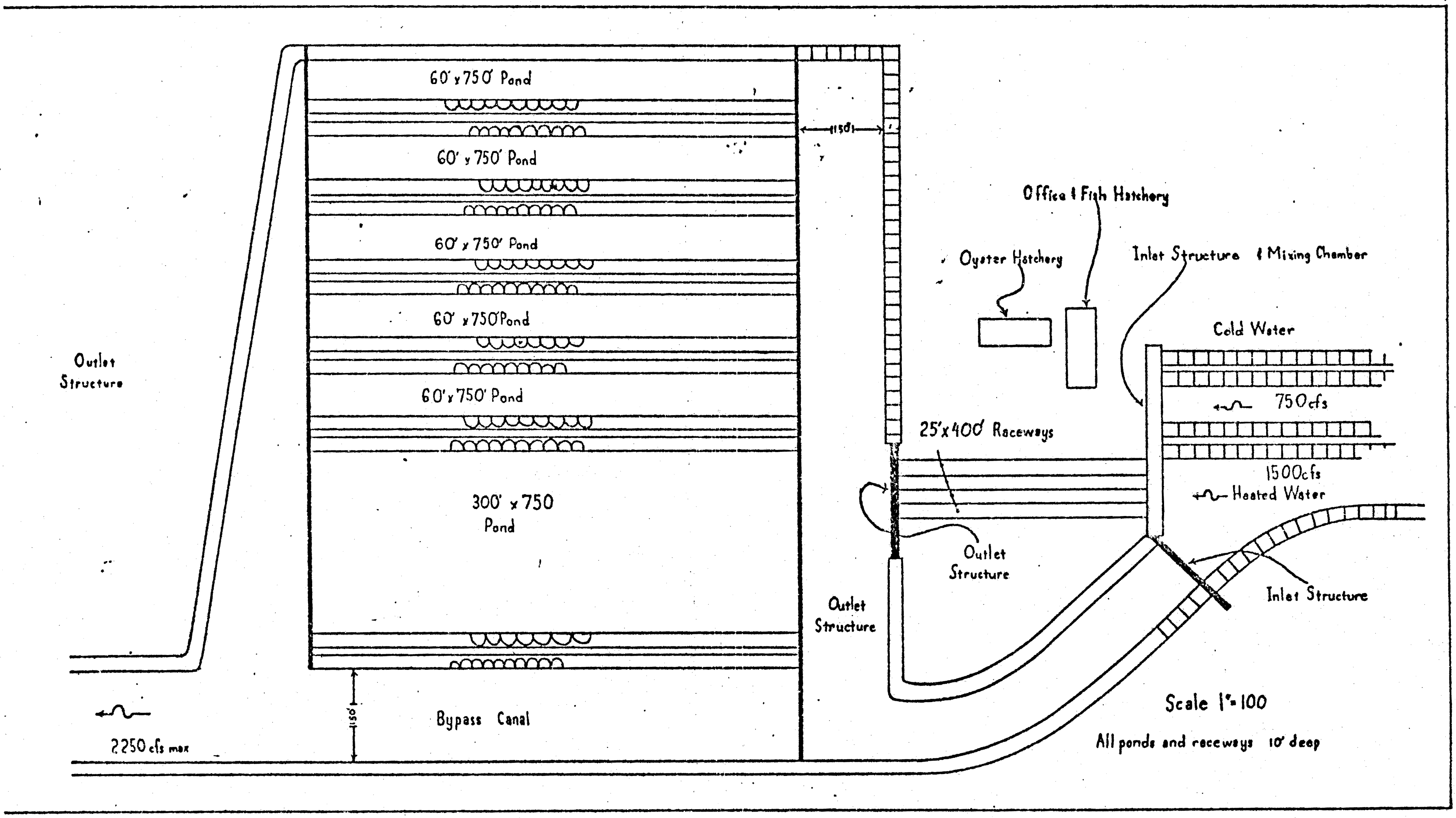

Figure 3. Maricultural pilot plant facility using the heated effluent from a power plant.

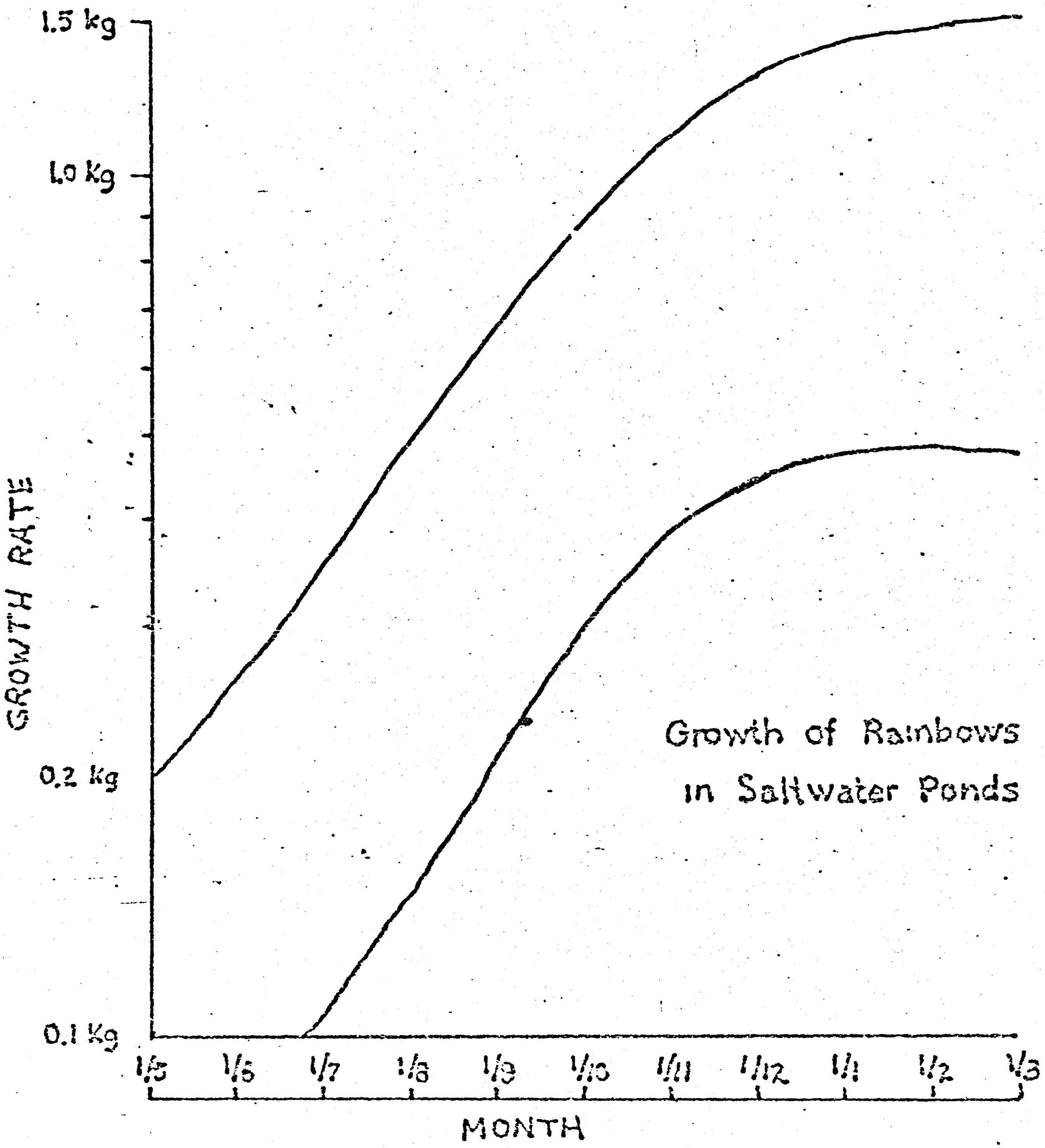

Figure 4. Growth of rainbow trout in saltwater ponds (From Jensen-1967)

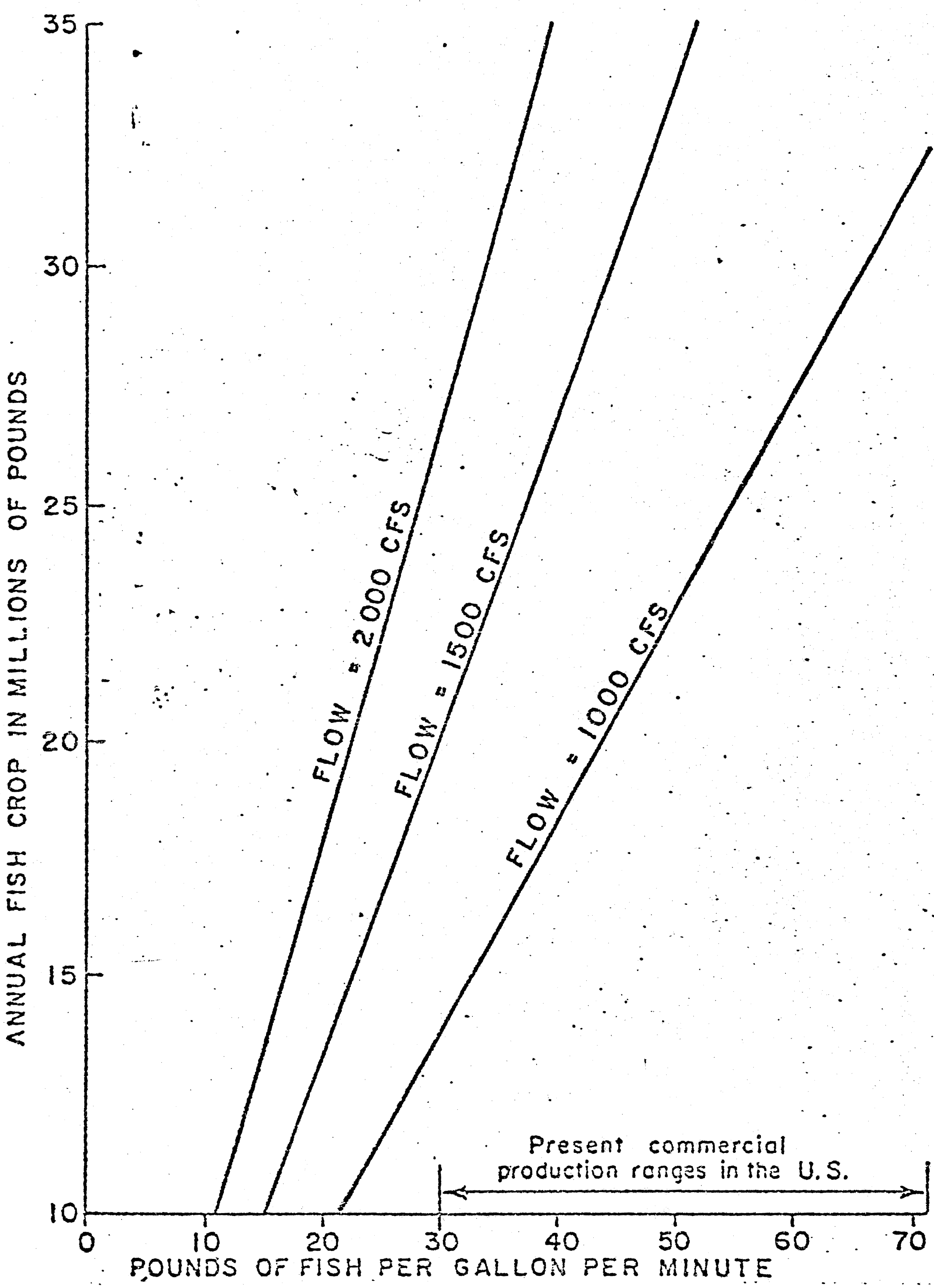

Figure 5. Possible annual yields of salmonid type fishes in raceway cultures utilizing heated effluents (From Novotny - 1968).

24 lbs per yard of rope. Paz-Andrade (1968) reported comparable yields. The ropes are suspended 20 to 28 inches apart and the mussels will grow to about 3 inches long in 12 to 18 months. According to my calculations, if ropes 11 yards long were suspended 40 inches apart (roughly 4 ropes per square yard), the annual mussel production would be 2,137 tons per acre. The proportion of weight of drained meat to total weight will range from about 25% to 50%, depending on the season in which they are harvested.

Nash (1968) fed his flatfish a steady diet of mussels at a rate of 10% of the biomass per day. If we relate this to full scale trout production of a 1,000-MWe thermal system (with an average biomass equal to 1/2 of the total annual crop, or roughly 1,650 tons), it would take 165 tons of mussel meat per day. Assuming a minimum meat yield of 25%, a year's supply of mussel feed for this system could be produced in about 125 acres of rafts, which could probably be incorporated within the entire mixed energy system--if sufficient space were available and if mussel seed could be produced at the proper time. Large ponds of mussels would also contribute to a multi-culture system, as organisms such as holothurians could utilize the great quantities of fecal material produced by mussels. This material is also valuable as a fertilizer.

Production of mussel seed could be important for use both within and without the system. Puget Sound, for example, appears to be rather similar in salinity, temperature, current flow, and primary productivity to the bays of Galicia, Spain. Joyner and Spinelli[2/] are presently reporting on a simple process of producing high quality protein concentrate from Mytilus edulis from Puget Sound. The concentrate has no offensive odor or flavor and has a protein efficiency ratio (PER) higher than casein and comparable to that of fish protein concentrate. A byproduct of the process is ground shells which can be used to make lime. About 6 1/2 lbs of mussel protein concentrate can be produced from 100 lbs of whole mussels. This means that 100 acres of mussel rafts could produce about 13,750 tons of protein concentrate per year.

This is on a scale of obvious significance to the problem presented by the world's shortage of protein.

ECONOMICS

Few mariculturists or engineers today have had sufficient experience in mariculture in mixed energy systems to make accurate economic cost-benefit analyses. Nevertheless, we can make some gross estimates of cost-benefit values for a pilot thermal energy system.

Table 1 is a cost estimate for the construction of the 16-acre pilot plant shown in Figure 3. Table 2 is an analysis of the dollar benefits that should be derived from such a system. On the basis of this analysis, the cost of the pilot plant should be amortized after 3 to 4 years.

2/ Joyner, T., and J. Spinelli. Mussels, a neglected source of marine protein. Bur. Commer. Fish., 2725 Montlake Blvd. E., Seattle, Wash. Manuscript.

TABLE 1. 16-ACRE MARICULTURE PILOT PLANT FOR SALT-WATER COOLED 1,000-MEGAWATT STEAM ELECTRIC SYSTEM

Cost Estimate

BUILDINGS:	
Office and fish hatchery - 4,400 sq ft at $50 =	$ 220,000
Oyster hatchery 4,400 sq ft at $40 =	176,000
EARTHWORK:	
Buildings, raceways and ponds -	240,000
Canals	410,000
CONCRETE STRUCTURES:	
Main inlet structure -	155,000
Raceways -	530,000
LARGE PONDS:	
Inlet structure -	420,000
Outlet structure -	335,000
OUTSIDE PIPING:	
Freshwater well and pumps -	20,000
Hot and cold water supply lines -	60,000
Pumps -	15,000
Septic system -	4,000
MECHANICAL:	
Freezer equipment -	10,000
Standby generator -	10,000
Filters -	20,000
ELECTRICAL:	
Complete wiring -	35,000
ROADWORK:	100,000
LANDSCAPING:	20,000
ROCK RIPRAP:	150,000
LAB EQUIPMENT:	100,000
TOTAL	$3,030,000

TABLE 2. ANNUAL DOLLAR BENEFITS FROM PROPOSED AQUACULTURE FACILITIES AT SALTWATER-COOLED STEAM-ELECTRIC POWER PLANT

Acreage		Depth
Oyster production	10.3	10'
Fish production	5.4	10'
Oyster seed		
225,000 strings at $1.92/string 1/		$432,000
Mature oysters		
112,500 gallons at $3.00/gallon 2/		375,000
Rainbow trout		
6,750,000 lbs 3/ at $0.06/lb 4/		405,000
	Total	$1,212,000

1/ Based on 1968 price paid by Washington growers for Japanese seed.

2/ 1968 price (in the shell) paid to Washington growers.

3/ Based on 10 lbs/gal/min of available water flow.

4/ Estimated profit based on 10% of price paid to grower.

SUMMARY AND CONCLUSIONS

Between 1969 and 1973, the United States will spend about $7.4 billion for municipal sewage waste treatment plants and $1.8 billion in controlling thermal wastes from new power plants (Environ. Sci. Technol., 1968a). At the same time, the world will be preparing to face the last quarter of this century with a definite threat of hunger. A great deal of promise lies in the large scale conversion of nutrient energy from sewage waste and the waste thermal and mechanical energy from power plant discharge water into edible protein through mariculture. Based on the intensive culture of rapidly growing shellfish and finfish such as trout, eventual production from these systems will be measured in hundreds or thousands of tons per surface acre and hundreds of pounds per cubic foot of flow.

A great need exists for mariculturists and engineers to work together to design such systems; for geneticists to develop optimum strains of organisms for each area; for pathologists to solve the inevitable disease problems; and for nutritionists to develop high quality feeds capable of being produced in sufficient bulk to supply such systems.

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