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ANALYSIS OF ECONOMIC AND ENERGY UTILIZATION ASPECTS FOR WASTE HEAT AQUACULTURE*

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ABSTRACT

A waste heat aquaculture system using extensive culture techniques to produce fin and shellfish is currently under investigation at the Oak Ridge National Laboratory. The system uses nutrients in waste water streams to grow algae and zooplankton which are fed to fish and clams. A tilapia polyculture association and the freshwater clam *Corbicula* are the animals cultured in the system.

The investigations detailed in this study were performed to determine the economic feasibility of the system and examine energy utilization in the system. A net energy analysis was performed to identify the energy saving potential for the system. This analysis includes all energy costs (both direct and indirect) associated with building and operating the system.

The results of the economic study indicated that fish production costs of \$0.55/kg (\$0.25/lb) were possible. This cost, however, depends upon the fish production rate and food conversion efficiency and could rise to as much as \$1.65/kg (\$0.75/lb). Clam production costs were found to be in the neighborhood of \$0.37/kg of clam meat (\$1.24/bushel).

The energy utilization study results indicated that, when all energy costs are included, fish from the aquaculture system may require only 35% of

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DISCLAIMER

the net energy now required for fish products from the ocean. However, the energy requirements also depend on system parameters and could be as large as the energy required for ocean caught products. Clams can be produced in the aquaculture system using only about 25% of the net energy required by traditional means.

The results of the analysis indicate that the system appears to be economically feasible. They also indicate that significant energy savings are possible if waste heat aquaculture products replace ocean caught products.

INTRODUCTION

Various techniques have been proposed and studied to utilize the heat contained in power plant condenser cooling water streams. These applications have focused primarily on agricultural (greenhouse and livestock facility heating, and open field undersoil heating) and aquacultural applications. Comparative analysis (1) of these systems has indicated that the most promising application appears to be an extensive aquaculture system being studied at the Oak Ridge National Laboratory. This system (described in a succeeding section) utilizes extensive aquaculture techniques to produce fin and shellfish.

Preliminary analysis (2) of the waste heat aquaculture system indicated that the overall system was technically and economically viable. However, these investigations were basically performed to determine the potential for the system to utilize reject heat. It appeared that an analysis to determine the economic viability of the system as an aquaculture enterprise was required. It also appeared that an analysis of the energy savings potential for the waste heat aquaculture system would be beneficial. This paper details the results of these analyses.

SYSTEM DESCRIPTION

The aquaculture system was designed to use extensive culture techniques and natural ecosystem food supplies. Fin and shellfish that feed on the lower trophic levels of the food chain were utilized in the system. Addition of waste heat was used to provide regulated growth temperatures for phytoplankton and zooplankton cultures and for the fish systems. Planktonic growth is further enhanced by the addition of nutrients available from a variety of waste streams. The planktonic biomass is used as the food source for fish culture, and polyculture techniques are employed to utilize all feeding niches in the pond. The basic system features (extensive polyculture, planktonic food sources, etc.) were chosen in an effort to keep production costs at a minimum.

Biological systems proposed for the waste heat aquaculture facility have been based on the following assumptions: (a) a minimum temperature of 20°C (68°F) can be maintained through the year, (b) a controlled input of nutrients (carbon, nitrogen and phorphorous) is available, and (c) mud bottomed ponds, 1 to 2 m (3 to 6 ft) deep, are used for the fish growth pond. Assumption (a) essentially envisions utilization of waste heat from a power plant using a closed loop cooling system. For this study, the species selection concentrated on fresh-water varieties because the majority of power plants are located inland. It should be noted, however, that suitable species (such as striped mullet, croaker, tarpon, and sheepshead) are available for coastal sites.

The general design features of the system are illustrated in Fig. 1. Conceptually, the system functions in the following manner. A nutrient stream flows into Pond I with an appropriate amount of diluent. Algae begin the uptake of nutrients, in Pond I, and are grazed upon by zooplankton. The

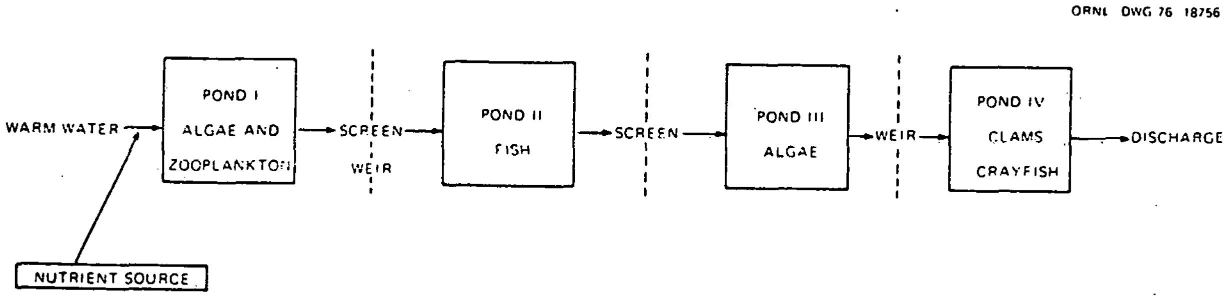


Fig. 1. Schematic diagram of waste heat aquaculture system.

overflow from Pond I, laden with algae and zooplankton, flows into Pond II where fish are grown. In Pond II fish consume algae, zooplankton, aquatic macrophytes (grown in the pond mud bottom) and benthic organisms. Water flows into Pond III laden with fish waste products, and algae are again used to remove the nutrients. In Pond IV clams are used as living biofilters, straining algae and bacteria from the water. Crayfish are used in Pond IV to consume the clam wastes. Protein production is concentrated in fish and clams.

The ponds are kept at or near optimum growth temperatures using power plant waste heat. It was assumed that plastic heat exchangers were used to transfer heat from the condenser cooling water to the aquaculture system. They were included to protect the aquaculture system from any contaminants present in the power plant cooling water.

A number of alternative biological associations is available for Pond II. Initial studies concentrated on carp and tilapia associations. Because of marketing considerations, it appears that tilapia have the greater potential for near term consumer acceptance. Therefore, this study concentrated on the tilapia association. This association encompassed several species and included: Nile (*Nilotica*), Java (*Mossambicca*), Blue (*Aurea*) and Congo (*Rendalli*) tilapia.

SYSTEM ANALYSIS

Analysis of the system included economic and energy utilization factors. The economic analysis was performed to determine the production costs for the various system products. An energy utilization analysis was also performed to determine if the waste heat aquaculture system used less energy than traditional methods of supplying fish products. This analysis was performed using the technique of process energy analysis, which includes all energy costs (both direct and indirect) of building and operating the system.

The overall system was subdivided into two subsystems: a fish production system and a clam production system. These subsystems were analyzed individually to give the reader a detailed description of the analysis method. Using the method presented in this report, any combination of fish and clam production subsystems can be assembled and analyzed.

Since the crayfish do not represent a significant economic input to the system, they have been omitted from the study.

DESIGN PARAMETERS

Previous investigations (3) suggest that water quality from the fish growth pond is sufficient to meet all EPA discharge regulations except the suspended solids limit. This criterion is apparently violated because of algae not consumed by the fish. Thus the clam system can be designed and operated in any of several ways depending upon its function in the overall system. If the clam system is used only to filter the remaining algae from the fish pond discharge stream, Pond III can be eliminated from the design. In this mode of operation the clam system is used strictly as an effluent polishing system. However, if maximum clam production is desired, additional algae must be supplied to the clam culture. In this instance the design of the system is given in Fig. 1. It was assumed that maximum clam production was desired. Therefore, Pond III was included in the system.

In designing the system, it was assumed that equal production (per unit area) of algae and zooplankton occurred in Ponds I, II, and III. Because of very short retention times in Pond IV, it was assumed that no significant algal production occurred there. Thus, all of the algae required by the clams was produced in the second algal growth pond (Pond III in the system design).

Design of the fish growth system (Ponds I and II) depended upon the fish production rate. If the algal production rate in Pond II was sufficient to meet the algal needs of the fish, Pond I was eliminated from the system. Otherwise, an algal growth pond (Pond I) — sized to provide the additional algal production required — was added to the system.

Fish production rates for tilapia systems of this type have not been firmly established. Annual yields of 7378 kg/ha (6500 lb/acre) have been reported for tilapia grown in sewage enriched ponds in Africa (4). Preliminary investigations at ORNL suggest that a yield of 85,125 kg/ha (75,000 lb/acre) is possible if sufficient algae is provided (5). Because of these fish production uncertainties, the system was analyzed over this range.

Food conversion rates are similarly unknown. However, it is generally accepted that conversion efficiencies of 10% (wet weight feed to wet weight fish) are typical when moving from one trophic level to the next. Assuming the algal feed is approximately 80% water and using a 10% conversion efficiency yields a food conversion ratio of 2:1 [2 lb (dry weight) algae converted to 1 lb (wet weight) of fish]. Since there are a number of uncertainties in arriving at this ratio, the system was analyzed using food conversion ratios of 2.5:1 and 5:1.

From values reported in the literature (6) it appeared that average algal production rates of 10 to 20 gr/m^2-day (90 to 180 lb/acre-day) are achievable if sufficient nutrients are available. Since it was assumed that sufficient nutrients were available from waste streams, the system design was based on an average daily algal production rate of 15 gr/m^2 (135 lb/acre).

Based on the above assumptions, the required algal pond sizes were computed for a 0.4 ha (1 acre) fish growth pond. These results are shown in Table 1.

Table 1. Algal pond sizes for one acre (0.4 ha) fish pond

Fish production rate (lb/year)	Food conversion ratio	
	5:1	2.5:1
	Algal pond size (acre)	
6,500	—	—
10,000	0.01	—
25,000	1.53	0.27
50,000	4.05	1.53
75,000	6.58	2.79

Clam culture production yields are not readily available, therefore, oyster culture yields were used as the basis for estimating production. A study at Woods Hole Oceanographic Institute (7) indicated that, under proper temperature conditions, oyster meat production could reach 417,680 kg/ha-year (184 tons/acre-year). These results were obtained for oysters grown on trays in aerated raceways and fed algae cultured using secondary sewage effluent. Because of the uncertainties in applying this data to clam production, it was felt that an annual clam meat production of 1.3×10^5 kg/ha-year (50 tons/acre-year) was reasonable.

These studies have also indicated that clams excrete some 30 to 70% of their food intake. Therefore, a food conversion ratio of 2:1 was used in the analysis.

The above assumptions resulted in a 0.83 ha (2.06 acre) algal pond required to support a 0.40 ha (1 acre) clam pond.

In designing the system, it was assumed that negligible algae flowed into Pond III from Pond II. Therefore, for the purposes of this analysis, the two systems (fish production and clam production) were considered to be independent. Since it was assumed that there is no algae carryover from Pond II to Pond III, the algal production pond was sized larger than would probably be required. This adds to the clam production cost and makes the results of the economic and energy analyses conservative.

The plastic heat exchanger was designed to transfer 7323 kW/acre (25×10^6 Btu/hr-acre) to the ponds. An overall heat transfer conductance of 369 W/m^2-°C (65 Btu/hr-ft^2-°F) and a log mean temperature difference of 5.7°C (10.2°F) were also used. The heat exchanger material is a polypropylene copolymer in the form of an extruded honeycomb.

ECONOMIC ANALYSES

The costs to construct the mud bottom ponds were based on constructing them using bulldozers to push up levees. A summary of the capital cost for a 0.4 ha (1 acre) fish pond is given in Table 2. Capital costs for a 0.4 ha (1 acre) clam pond and a 0.4 ha (1 acre) algal pond are also given in Table 2.

Table 2. Capital cost summary for one acre (0.4 ha) ponds

Item	Fish pond cost ($)	Clam pond cost ($)	Algal pond cost ($)
Pond construction	535	535	535
Fish handling equipment	1000		
Clam racks and other equipment		560	
Pump	160		195
Subtotal	1695	1095	730
Contingency (@ 30%)	515	329	220
Total	2210	1424	950
Annual fixed charges (FCR 15%)	332	214	143

Since the material cost for the heat exchanger plastic panels is $1.90/m^2 (\$0.24/ft^2), a fabricated heat exchanger cost of \$8.07/m^2 of heat exchange area (\$0.75/ft^2) was used in the study. This resulted in a capital cost of \$10,800/ha (\$27,000/acre) for the heat exchanger.

These capital costs were annualized using a fixed charge rate (FCR) of 15%. The fixed charge rate includes return on investment, capital item depreciation, taxes, insurance, project lifetime and a number of other items. Using an FCR of 15% for a project with a 20-year lifetime yields a return on investment of 8%. For the purposes of this study, tax credit considerations were not included in the FCR. Including an investment tax credit of 10% (which is typical) yields a return on investment of about 14%. Thus, neglecting the tax credit results in a conservative economic analysis. A summary of the annual fixed charges for each pond system is given in Table 3. Applying the fixed charge rate to the heat exchanger yielded an annual fixed cost of \$4051.

Table 3. Summary of annual operating costs for one acre (0.4 ha) ponds

Item	Annual cost (\$/acre-year)		
	Algal ponds	Fish ponds	Clam ponds
Electricity	43	54	30
Management and maintenance	500	460	220
Stocking		0.03 × fish production rate	4000
Total	543	514 + (0.03) × fish production rate	4250

Operating costs for the subsystems are summarized in Table 3. As previously stated, the fixed charge rate includes tax and insurance considerations. Therefore, it was not necessary to include them in the annual operating cost breakdown. It was assumed that the heat exchanger required very little maintenance, and the annual operating cost was neglected.

The total annual fish and clam production costs were obtained by summing the annual fixed charges and the annual operating costs, from Tables 2 and 3, to give the total annual cost for each of the system components. These costs were then applied to the system designs, described in the previous section, to yield the total annual fish and clam production cost. A summary of the annual fish production costs is given in Table 4.

Table 4. Annual cost summary for fish production system

Food conversion ratio	Fish production (lb/year)	Annual cost ($/year)			
		Algal pond	Fish pond	Heat exchanger	Total
5:1	6,500	—	1041	4,051	5,092
	10,000	7	1146	4,092	5,239
	25,000	1048	1596	10,249	12,893
	50,000	2774	2346	20,458	25,578
	75,000	4507	3096	30,707	38,310
2.5:1	6,500	—	1041	4,051	5,092
	10,000	—	1146	4,051	5,197
	25,000	185	1596	5,145	6,926
	50,000	1048	2346	10,249	13,643
	75,000	1911	3096	15,353	20,360

Dividing the annual costs from Table 4 by the fish production rate yields the unit fish production cost. These results are plotted in Fig. 2.

Summing the costs associated with the clam production system gives a total annual cost of $18,273. Dividing this by the clam yield gives a production cost of $0.41/kg ($1.32/bushel).

NET ENERGY ANALYSIS

The energy required, directly and indirectly, to produce fish and clams by the aquaculture method described has been estimated and compared with the energy used in harvesting an equal amount of fish and clams by conventional

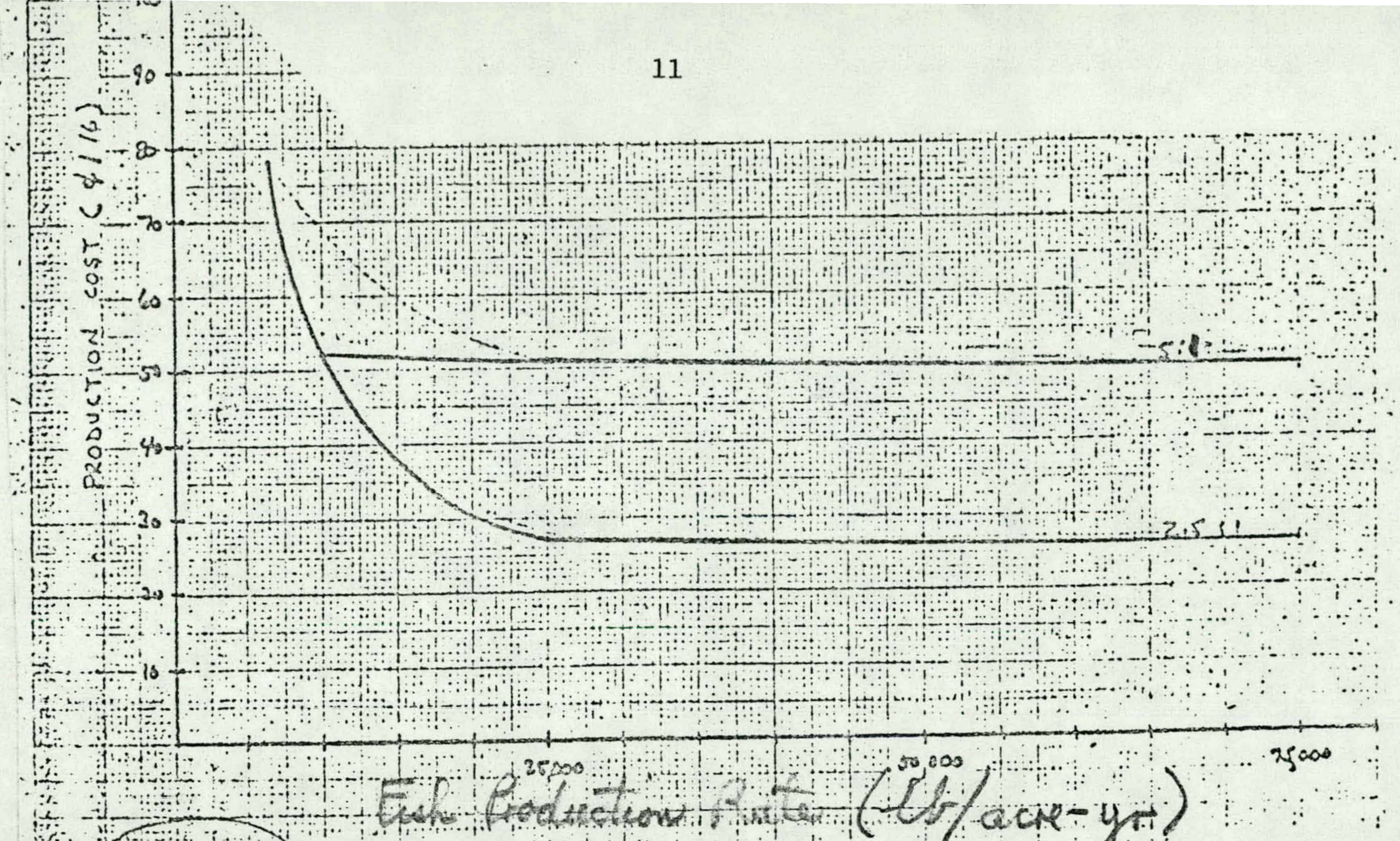


FIG 2

FISH PRODUCTION COSTS ASSUMING ALGAL PRODUCTION OF 135 lb/ACRE-DAY WITH EQUAL ALGAL PRODUCTION IN THE FISH AND ALGAL POND WITH NO CIRCULATION PUMP IN THE ALGAL POND

FOR 15%

fishing and clamming. The electrical energy required for operating the pumps is estimated directly from the projected water flow rates and pressure heads. Other direct and indirect energy requirements, such as those for pond construction, heat exchanger fabrication and installation, and labor, are calculated using tabulated net energy intensities. The energy intensity, defined as the energy required to make a dollar's worth of products or services, has been calculated from economic census data and tabulated for each major economic sector (8). For example, in 1967 a dollar's worth of concrete products required 117.2 MJ (117,234 Btu). This includes all energy expended from the time when the constituents were in the ground as minerals through the final fabrication. Energy embodied in machinery or facilities used, in supplies consumed, in transportation, etc., is included. The energy required for each portion of the aquaculture installation has been calculated using the energy intensity for the broad economic sector which corresponds best to it.

A summary of the energy requirements determined in this manner is given in Table 5. The net energy of the feed stream and the discharge water stream are assumed to be free inputs and are not included. In addition, each acre of pond requires 1908 GJ (1908 million Btu) for the heat exchanger.

Table 5. Net energy requirements for one acre (0.4 ha) ponds

Item	Millions of Btu		
	Fish pond	Clam pond	Algal pond
Construction	27.21	27.21	27.21
Pump	4.77		5.78
Equipment	36.85	18.42	
Total capital	68.83	45.63	32.99
Annual electricity	37.48	20.82	29.85
Annual labor	19.49	9.32	21.19
Total annual operating	56.97	30.14	51.04
Fingerlings, Btu/lb product	720		
Seed clams, Btu/lb product		1382	

The energy requirements in Table 5 are used with the pond areas in Table 2 to calculate the total energy requirements for fish production. The results are given in Table 6. The energy needed to obtain an equal amount of fish by conventional fishing, estimated at 52.9 GJ/kg (24,000 Btu/lb), is also shown. The last column of Table 6 gives the ratio of the net energy required by extensive aquaculture to that required by conventional fishing. These numbers suggest that, for large enough production rates, aquaculture may produce fish at considerably lower net energy expenditures than fishing.

A similar calculation for the one-acre clam pond described above shows that it will require 11.4×10^6 GJ (11.4×10^{12} Btu) over its 20-year lifetime. The energy required to produce an equal quantity of clams by clamming is estimated at 48×10^6 GJ (48×10^{12} Btu).

Table 6. Net energy summary for fish production system
1-acre (0.04 ha) fish pond
20-year life
135 lb algae/acre-day

Food conversion ratio	lb/year fish produced	Total energy required (MMBtu)	Energy equivalent of product (MMBtu)	Ratio required/production
5:1	6,500	3,208	3,120	1.03
	10,000	3,288	4,800	0.69
	25,000	7,996	12,000	0.67
	50,000	15,826	24,000	0.66
	75,000	23,668	36,000	0.66
2.5:1	6,500	3,208	3,120	1.03
	10,000	3,259	4,800	0.68
	25,000	4,275	12,000	0.36
	50,000	8,366	24,000	0.35
	75,000	12,456	48,000	0.35

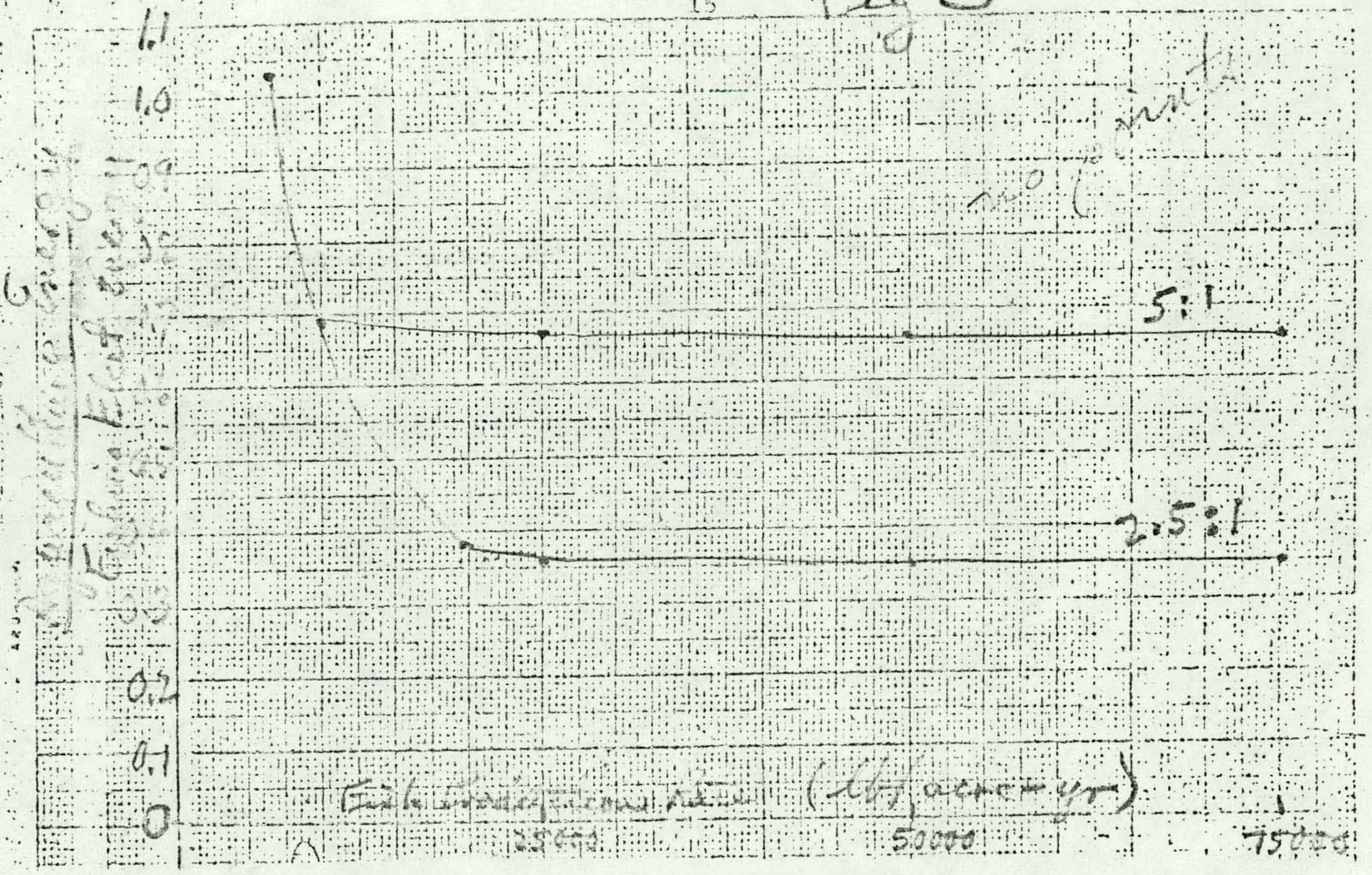
DISCUSSION OF RESULTS

The system economic analysis results in Fig. 2 indicate that the tilapia can be produced for $1.10 kg (50¢/lb) or less if the annual fish production rate is above 11,350 kg/ha (10,000 lb/acre). Recent marketing information (9) has indicated that a round-weight, pond-bank price of $1.21/kg (55¢/lb) is reasonable. Thus it appears that the tilapia production system is economically viable. Similarly, the clam production costs are well below current clam prices. Thus the clam production system is also economically viable.

The net energy analysis indicated that each subsystem had the potential to yield products at substantially reduced total energy inputs. Thus, it appears that the total system design can be adjusted according to local market conditions without adversely affecting either the economic viability or energy savings potential for the system.

It should be noted that the net energy requirements obtained from the tables and those estimated for fishing are subject to large uncertainties. The estimates, in some cases, may be in error by as much as 50%. Because of this, the net energy savings achievable through the use of aquaculture, presented in Fig. 3, should only be used for comparative purposes. Even with these uncertainties, however, it appears that the aquaculture system is more energy effective than traditional fish and clam supply methods.

Fig 3



As noted above, several biological parameters must be determined before a definitive assessment of the system can be made. Research efforts will begin this summer in an effort to determine these parameters. These studies will also examine system culture techniques and explore dynamic control considerations.

CONCLUSIONS

The fish and clam production subsystems appear to be economically viable. It also appears that each subsystem has the potential to yield products at substantially reduced energy inputs (when compared to traditional methods of supplying these products).

Research work should be undertaken to define some of the unknown biological parameters. With this information a definitive assessment of the system can be performed.

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