Advances in closed (recirculated) system mariculture

by

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Abstract: Man has practiced various forms of aquaculture for thousands of years. Most of his efforts have been directed toward manipulation of natural systems. However, experience in agriculture, which has had the technological advantage of several hundreds of years of developmental effort, has shown that certain crops (poultry, winter tomatoes, mushrooms, flowers, etc.) are best produced in artificial or otherwise highly controlled environments. It has become apparent to us at Delaware that such may be the case with bivalve filter-feeding shellfish.

Based on the success of artificial propagation in agriculture, scientists at the University of Delaware decided to attempt to raise marine shellfish in a closed or recycled system having a high degree of environmental control. The long-range collective objective of Delaware's maricultural research is to produce successfully, on algal and/or prepared foods, desirable, fastgrowing, palatable, nutritious oysters and clams, free of toxins and pathogens, in a controlled environment seawater system, at reasonable cost, unhampered by legal constraints, using natural sources of energy, and recycling organic wastes.

Introduction of new strains of shellfish and the successful exploitation of existing ones would provide the basis for the establishment of a new shore-based marine food industry. The University of Delaware College of Marine Studies maricultural program on the Lewes campus, was instituted to develop an economically and technologically viable prototype for industrial adaptation.

HISTORICAL BACKGROUND

Man has practiced various forms of aquaculture for thousands of years. Most of his efforts have been directed toward manipulation of natural systems. However, experience in agriculture, which has had the technological advantage of several hundreds of years of developmental effort, has shown that certain crops (poultry, winter tomatoes, mushrooms, flowers, etc.) are best produced in artificial or otherwise highly controlled environments. It has become apparent to us at Delaware that such may be the case with bivalve filter-feeding shellfish.

During the late 1800's, Delaware Bay produced 23 million pounds of oysters (the eastern oyster, *Crassostrea virginica)* and had substantial shad, sturgeon, and

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other fisheries. Due to a variety of factors, including improper management of shellfish beds (harvesting without replenishing equal quantities of shell stock), development of the watershed with attendant siltation, heavy industrialization of the Delaware River, industrial effluents and oil spills, mosquito control by ditching wetlands and spraying, and closure of harvesting areas due to sewage contamination, oyster production declined steadily to 9 million pounds by 1954. By 1960, the oyster industry in the Delaware Bay region suffered a catastrophic collapse due to a parasitic haplosporidean protozoan, familiarly known as MSX *(Minchinia nelsoni)*. In Delaware, the value of oyster landings declined from almost $3 million to less than $40,000 in the period from 1954 through 1961. The fishery has not been reestablished to date (Maurer *et al.*, 1971).

What has happened to the oyster in the Delaware is an omen of what could happen to fisheries in other estuaries and in other environments. The decline of the menhaden *(Brevoortia tyrannus)* industry and the imminent threat to the surf clam *(Spisula solidissima)* fishery are poignant exarnples on the east coast of the U.S.A.

Based on the success of artificial propagation in agriculture, scientists at the University of Delaware decided to attempt to raise marine shellfish in a closed or recycled system having a high degree of environmental control (Fig. 1). The long-range collective objective of Delaware's maricultural research is to produce successfully, on algal and/or prepared foods, desirable, fast-growing, palatable, nutritious oysters and clams, free of toxins and pathogens in a controlled environment seawater system, at reasonable cost, unhampered by legal constraints, using natural sources of energy, and recycling organic wastes. Introduction of new strains of shellfish and the successful exploitation of existing ones would provide the basis for the establishment of a new shore-based marine food industry. The Delaware Sea Grant College maricultural program on the Lewes campus of the College of Marine Studies was instituted to develop an economically and technologically viable prototype for industrial adaptation (Maurer, 1972; Pruder *et al.*, 1977).

CLOSED (RECIRCULATED) SYSTEM vs. OPEN SYSTEM MARICULTURE

Mariculture has developed to a highly sophisticated state in Japan and several other foreign countries, the approach being characterized by:

1. Manipulation of open natural systems using rafts, long lines, pens, and ponds for culturing a broad range of marine species.
2. Adequate sources of inexpensive hand labor.
3. Adequate sources of inexpensive animal feeds.
4. Strong need for maricultural products predicated on ethnic and economic considerations.

Mariculture has not been particularly successful from an economic standpoint in the United States because, with the exception of Item (1), the aforementioned conditions do not exist there.

However, closed or recirculated mariculture systems potentially can avoid the need for hand labor and can provide inexpensive nutritious animal foods on a dependable basis using sunlight as the primary source of energy.

The distinct advantages of closed system mariculture vs. open system mariculture are shown in Table I.

Table 1

WHY CLOSED-CYCLE MARICULTURE?

	Closed Cycle	*Open Cycle*
LENGTH OF GROWING _SEASON	Optimal growing temperatures can be maintained year-round with minimal energy and expense due to recirculation of the growth media:	Energy costs are extremely high due to once through heating and cooling of the growth media. The alternative is no temperature control which tends to lengthen the growing season for the crop in question in temperature latitudes.
FEED	Foods can be fed at higher densities than in nature and can be selected for nutritional suitability for the mariculture crop.	Phytoplankton densities generally are relatively low and highly variable in nutritional quality and quantity.
WATER OUALITY	Water quality parameters may be optimized to promote maximum health and growth in the mariculture crop.	Water quality parameters, such as oxygen levels and salinity, may vary in an uncontrollable fashion.
PURITY	Contaminants, such as chemicals and human and shellfish pathogens, can be avoided and/or treated if need be.	Little or no control can be exercised over contaminants.
RAW MATERIALS	Food and other growth factors can be recirculated to conserve raw material input into the system and, therefore, cost of these materials can be controlled.	Food and other growth factors can be lost to the system if the animals do not assimilate them in a timely manner.
ENERGY	Good potential exists for harnessing solar energy for growing food and other energy requirements in the system.	Although solar energy is available as an input, it is difficult to manage in an open system.
LOCATION	The system may be located anywhere as long as seawater or sea salts can be shipped to that location. Recirculated systems require relatively small amounts of make-up water.	Must be located on the coast where competition for use of space and water may be prohibitively expensive.
LABOR	Substantial potential exists for mechanization and automation reducing need for hand labor.	Due to husbandry and level of technology, substantial hand labor commitment is required.
OUTPUT	Reliable output rates are possible, based on year-round production that is not substantially affected by seasonal variations in climate.	Crops are seasonal and occasionally succumb to natural catastrophies, such as storm Agnes.

It is clear from these advantages that closed cycle mariculture holds the same relationship to open system mariculture as modern cattle feed lot and poultry husbandry operations have to allowing cattle and poultry to range for forage on an open range.

ADVANCES IN CLOSED (RECIRCULATED) SYSTEM MARICULTURE

With support from Sea Grant, the State, and industry, the University of Delaware team has been working to raise super shellfish–oysters and clams. Delaware proved not only that these bivalves can be grown in a closed system, but also that they grow faster than they would naturally. Oysters that take at least 36 months to mature in natural seabeds are now growing to market size in only 36 weeks in Delaware labs. The same degree of success has been achieved with clams, growing them to market size three to five times faster than in nature.

Since the program's inception, the record has been one of continuing progress.

1968-1970 Biologists concentrated on manipulating parents to spawn at will. The bivalves were grown initially using natural plankton in a flow-through system.

1970-1973 Clams and oysters reared in the laboratory were maintained in a recirculating system and fed various diets of algae, also grown in the lab. Clams grew 50 percent faster than they do in nature.

1974-1975 Delaware's team became the first group in the world to successfully grow clams and oysters to market size in a recirculating seawater system.

Today The system can now produce adult bivalves in less than a year from animals hatched and grown to maturity in the laboratory (Fig. 2).

Outstanding achievements have been made with the algae needed to feed the animals. Delaware's mariculture scientists can now produce thirty times as much algae in a given volume of water than could be produced in 1973. Also, they have determined several types of algae that promote fast growth of the bivalves.

SPECIFIC ACCOMPLISHMENTS

Research in mariculture at the University of Delaware was initiated in September, 1968, under the direction of Dr. K. Price and Dr. D. Maurer (Price and Maurer, 1969).

During the first three years (1968-71), success was achieved in conditioning broodstock, spawning parents at will, rearing larvae to setting, and growing oysters for six months on natural plankton (Maurer and Price, 1968; Price and Maurer, 1971; Keck, *et al.,* 1971; Maurer, 1972). Agricultural engineers fed starch and protein to oysters, but with little success (Dwivedy, 1972). Small recirculating systems were constructed, but chemical data were insufficient to gauge performance of the systems, and survival of oysters was poor (Dwivedy, 1973, 1974).

During the fourth year (1971-72), under the charge of Dr. C. Epifanio, improved methods for setting of larvae were explored, methods for prevention of gas bubble disease were developed (Malouf *et al.*, 1972), and an assimilation efficiency study of oysters fed on the alga, *Phaeodactylum*, was completed. An engineer, Mr. G. Pruder, joined the team and most of the design and construction of the current Maricultural Laboratory was completed and a specification manual was published (Pruder *et al.*, 1973). The first two recirculating systems were built, loaded with finfish, and monitored for chemical data (Srna *et al.*, 1973). In addition, preliminary experiments were directed toward maintaining the blue crab *(Callinectes sapidus)* in a recirculating culture system (Winget, *et al.*, 1973, 1976).

During the fifth year (1972-73), an algal culturist joined the group and the algal culture system currently in use was established. Postlarval clams and oysters reared in the laboratory were maintained in recirculating seawater and fed different diets of cultured algae; growth of the clams during the first six months was 50 percent faster than in nature (Hartman *et al.*, 1974). Two more large recirculating systems were constructed. Dr. R. Srna, a physical chemist, joined the team and the current water-quality laboratory was established and the use of an ammonia electrode was demonstrated in seawater analyses (Srna *et al.*, 1973). Alkalinity problems in the recirculating system were identified, and a solution was implemented (Epifanio *et al.*, 1973).

During the sixth year (1973-74), growth studies of clams and oysters fed selected species of laboratory-raised algae in recirculated seawater continued, and the shellfish approached market size. This was the first time anywhere that oysters and clams were grown successfully in a recirculating seawater system (Epifanio and Mootz, 1975). Preliminary biological specifications for construction of a commercial system were developed (Epifanio, Srna, and Pruder, 1975). Studies of tolerance of clams and oysters to their own waste products, particularly ammonia, were completed (Epifanio and Srna, 1975), and feeding rates of oysters were determined. The chemical kinetics of small-scale marine biological filters were characterized (Srna and Baggaley, 1975a), the use of chloride, calcium, and divalent electrodes to maintain major ion balance in recirculating seawater was demonstrated (Srna, 1974), the preliminary data on production of ammonia by active and sedated shellfish were collected (Srna and Baggaley, 1975b).

During the seventh year (1974-75), the following additional investigators were attracted to the maricultural program to fill in critical areas of investigation which were not covered. Dr. K. Biddle, prepared foods; Dr. J. Sharp, algal culture kinetics; Dr. M. Tripp, Dr. D. Herson, Dr. J. Noble-Harvey, and Dr. R. Gray, microbiology; Dr. E. Bolton, ozonization; Dr. F. Costello and Dr. R. Dick, engineering; and Mr. J. Bockrath, legal aspects of mariculture. Clams and oysters were grown to seed size in recirculating seawater systems and clams *(Mercenaria mercenaria)* and oysters *(Crassostrea virginica)* were raised to edible market size, exhibiting a growth rate approximately three times that of the fastest reported growth of the species in Delaware Bay. Studies of the assimilation efficiencies of clams and oysters fed different algal diets were begun, as were exploratory studies on preparation and feeding of formulated foods (Epifanio, 1976; Epifanio, *et al.*, 1975). Preliminary growth studies of four species of algae were carried out, and a study of nutrient utilization by a weed species and a good food species in chemostats relative to particulate carbon, nitrogen, and chlorophyll as a function of growth, was begun. Bacteria were isolated and characterized from algal cultures and recirculating seawater systems and correlated with water quality (Smith, 1977a, 1977b). Simulation of massive lysis of algal cultures using bacteria and their metabolic products was begun. A virus concentrator was constructed. Studies of nitrification kinetics and a new modular nitrification filter design were completed (Srna, 1975). A high density, small-scale recirculating seawater system was designed and constructed (Srna, *et al.*, 1976). A rate equation for metabolic production was integrated and solid wastes production rate experiments were initiated (Srna and Baggaley, 1975b; Srna, *et al.* 1975). Equipment and facilities were set up for bench-top studies on the application of ozonization in the treatment of maricultural fluids. Significant increase was obtained in mass algal production. The design and construction was completed and operation of a four-bushel shellfish closed-cycle prototype was begun (Pruder 1975). Design and construction of a 50-bushel prototype was started. Significant reductions were achieved in make-up water, waste treatment, and make-up nutrients in the small prototype. A study of legal problems of new product development for closed-cycle mariculture in the Delmarva region identified Delaware as being particularly suited to the establishment of commercial mariculture from the point of view of fishery law.

During the eighth year (1975-76), industry interest has been substantial, resulting in, a) eleven industries attending an MIT Opportunity Briefing at Delaware on closed system aquaculture, b) Unilever Ltd. entering into a three-year industry partner agreement with the University of Delaware involving a $45,000 commitment by Unilever to closed system research and development work, c) Campbell Soup Company agreeing to assist the University of Delaware in shellfish nutrition work by conducting nutritional analyses of bivalve shellfish feeds and contributing $45,000 to closed system research and development, d) direct laboratory participation in the Delaware project by Amoco (Standard Oil of Indiana) in providing alternate shellfish foods (yeast) for testing, and e) a considerable number of inquiries concerning the Delaware closed system mariculture program. Several patent disclosures concerning closed system shellfish culture have been initiated.

During the eighth year, we began testing a 50-bushel system on a natural day/night cycle in a simple greenhouse. A significant advance in algae culture has been achieved through a careful control of gas mixtures so as to repress photosynthetically wasteful photorespiration resulting in culture densities of six million/ml in a semi-continuous culture mode in 10,000 liter cultures. Monocultures may be sustained and harvested for periods of 2-3 weeks. Fifty mg dry weight of algae/liter may be harvested daily. This compares favorably with best average laboratory culture production. Recycle has been increased from 70 percent to 90 percent with only a minor reduction of oyster growth.

Water quality monitoring techniques were refined to levels currently used in the recirculated system. Seven diagnostic water quality parameters can now be routinely analyzed by a simple procedure at a number of stations through the process on a regular basis and a large chemical data base is being accumulated.

Rapid growth response technique provides results within a four week period for analysis of food and energy flow from algae species *Tetrasellmis suecicia* and *Pyramimonas* sp. clone PYR-2. Efforts are directed toward optimizing for nutritional quality of algae by selecting the optimal growth phase for harvesting.

Trace metal and mineral analyses in highly recirculated systems have now demonstrated that Ca and Fe are readily depleted. Significantly no toxic accumulations of metals have been detected.

Techniques for shell ultra structure in relation to growth in controlled recirculated systems have been established. Differences in the crystallinity of shell structure in controlled and wild oysters have been identified.

Macro-economic analysis of a potential shellfish production firm has been completed to arrive at an estimated price per individual. Already, some high cost items identified have been eliminated by biologists through further research.

Intensive routine macrobiological monitoring of all culture systems continues and to date no shellfish or human pathogens have been identified from the culture systems. Although an extensive protozoan fauna has been identified and associated with high organic loading, none has been pathogenic to shellfish.

ECONOMIC ASPECTS

Maricultured oysters differ enough from "natural" oysters to be classified as a new product for the purpose of predicting potential sales revenue. Initially there may be some hesitancy to buy a commercially raised oyster, but most of the unique characteristics of these oysters should increase their price relative to a commercially harvested one. Quality control will be better, a constant output can be guaranteed, and flesh per individual will be greater. (A bushel of maricultured oysters may contain up to as much as twice as much edible flesh.) How much of a price premium these attributes will bring is not known at this time, nor is the size of the potential market. For one thing, there are at least three possible types of markets to enter: the ex-vessel market, the standard wholesale market, or contractual arrangements with large commercial processors. There is a wide range between the prices in the first two markets ($6 to $20 per bushel in 1976) with the likely price for the third to be somewhere between them, depending on the bargaining ability of the producer and the processor. There is no real information at present as to just how big each of these markets is because there have been no formal studies nor have there been any large increases in natural production.

The National Marine Fisheries Service estimates that the price elasticity of oysters is .6728, which means that for every 1% of increase in output, price will fall .6728 %. Or to put it another way, if mariculture production were to increase output by 10%, the price would be about 6.7% less than it would be otherwise. But, of course, this does not take into account the positive attributes of maricultured oysters that may give them a premium price. In any event, what existing information there is does not indicate any apparent strong limits to the size of the market. Obviously, one cannot produce all the oysters one can and not have an effect on price, but there does appear to be room to grow, especially as transportation and marketing channels adjust to increases in supply. The latter statement is especially true if one considers the potential of the essentially virgin markets in the inland parts of the country and the fact that mariculture operations may be possible in those locations.

It is extremely difficult to predict unit costs of maricultured oysters simply because the exact process to be used has not yet been determined. We know what must be done and how to do it in the laboratory and in very small test operations, but not how best to adapt this to large scale operations so that cost per unit of output is minimized. The Delaware Sea Grant program is in the process of studying this very thing, but at the time of this writing no results have been obtained. A three-year old study using what appeared to be an efficient method, given the state of knowledge at that time, indicated that costs would be somewhere between $20 and $32 per bushel in today's dollars. (Given the improvements that have been made since this study, these cost estimates should more than likely be considered as upper limits.) So on a strict comparison with commercially harvested oysters, it appears as if mariculture will be potentially profitable. If maricultured oysters are indeed able to obtain a premium price, then things look even better.

RESEARCH NEEDS

Although Delaware's current research has shown that growing shellfish in closed or recycled systems is technically possible and that economic feasibility is within reach, a substantial amount of research and development remains to bring maricultural systems to the level of sophistication that has been achieved with agricultural systems.

A sample of the types of research and development activities that remain to be undertaken with shellfish include:

1. Maximum efficiency attainable in the use of sunlight by marine autotrophic organisms (i.e., food algae) as compared to the high efficiency of other land crops. This would include research on different food species, phases of the growth curve, various nutrient media, and other environmental conditions.
2. Maximum assimilation efficiency of algal foods by filter feeding such as oysters and clams, optimum age and density of algal cells when consumed; best species for feeding; unispecies or multispecies diets; nutritional requirements to produce most nutritional algal cells (minerals, vitamins?); effect of organic catabolites for algae on duration and rates of feeding by shellfish; methods of chemically enhancing the attractiveness of algal cells to filter feeding shellfish; methods of accelerating intake of food cells and stimulating digestion; methods of improving efficiency of digestion of algae cells by shellfish.
3. Methods for avoiding contamination of closed-cycle maricultural systems by poisonous algae (like the red tide forms *Gymodynium* and *Gonyaulax).*
4. Physical-chemical environment of closed-cycle maricultural systems: mineral nutrition; ionic composition of the natural seawater available; depletion of minerals by shellfish and their replacement in recycling seawater; mineral cycling through organismal chains (i.e., algae-shellfish); impact of physical and chemical perturbations of algae and shellfish as well as on the seawater itself; thermodynamic considerations (including kinetics, free energy, enthalpy, entropy); "water quality" as it is applied to mariculture; possibility of discovering a ratio of ions in seawater that oysters and clams would live in, but in which parasites and disease organisms would not; search for a simple formula of a minimum number of components which would satisfy osmotic requirements of shellfish and to which could be added the optimal quantities of supplements such as minerals and vitamins required by the shellfish; optimal requirements in salinity, temperature, oxygen, and CO_2 for ideal growth of shellfish—conditions which may not be those found in nature.
5. In genetics: breeding more nutritious, more acceptable, faster growing algal foods; breeding thinner-shelled bivalves with larger mantle cavities

and thicker mantles and other tissues that are fast growing, and more palatable to human consumers.

6. In behavior: effect of crowding of shellfish grown in closed-cycle maricultural systems on growth rate, shell size, and form, taste of meats, reproduction, spawning, etc.; response of shellfish to direction and rates of flow of seawater; determining why and when shellfish open to feed, or close; shellfish adaptability to vibration, varying photoperiods, various light intensities (photokineses); effect of elimination of such cyclic environmental phenomena as tidal cycles and lunar cycles from shellfish cultured in closed systems; effect of constant environmental conditions on the functioning of shellfish; search for alternate environmental conditions which might stimulate improved physiological activities (e. g., feeding, digestion, egestion, respiration, excretion); effect of conditions of closed-cycle mariculture on ingestion, formation of crystalline style, digestion, egestion, respiration, and excretion, possibility of reducing formation of pseudofeces.
7. Interrelation of shell deposition, i. e., shell growth, and fattening of meats; mineralogy of shell deposition in closed systems, i. e., ratios of calcite and aragonite; of mineral shell units and conchiolin; effect of varying concentrations of magnesium, strontium and manganese on shell composition.
8. Long term evaluation of raising algae and shellfish in artificial seawater to note effects on feeding rates, growth, quality of meats and production.
9. Gamete formation and spawning in closed systems, and methods of avoiding spawning in order to keep systems from being fouled by gametes; viability of gametes and development of young from shellfish grown in closed systems.
10. Chemical and taste qualities of shellfish grown in closed systems over long periods of time.
11. Chemical by-products from shellfish: feces, excretory products.
12. Toxicities; oyster and algal metabolites; leechings from physical system (plastics, wood, fiber glass).
13. Potential heterotrophic habit of marine autotrophs (as in *Euglena* which is facultative): in a prototype in the absence of sunlight or artificial light, food energy can be supplemented by addition of appropriate quantities of fixed carbon (e. g. glucose).
14. Role of bacteria, viruses, yeasts, fungi, protozoa, and other microorganisms in closed systems; beneficial effects in their improving the quality of the seawater or in their use as food; potential danger from pathogens and disease.
15. Optimal sterilization procedures in maricultural operations.
16. Optimal volumes of seawater (or artificial seawater) in closed systems; rates of flow, aeration; waste removal; effect on algae of using recycled seawater.
17. Optimal engineering configurations for shellfish production ranging from family-operated units to large scale industrial units.
18. The use of solar energy in the closed-cycle maricultural production of shellfish.
19. Optimization of energy use in the production of shellfish in closed systems.

20. Processing and packaging closed system maricultural products.

NEW FACILITY AND PERSONNEL

The University of Delaware recently took several steps to expedite the commercial viability of closed system mariculture. We have just been awarded a $1.2 million Economic Development Administration grant to build a new mariculture research facility at the University's Marine Studies Complex in Lewes, Delaware. The new laboratory, which should open in late fall of 1979, will provide about 24,000 sq. ft. – 11,000 for research, offices and services and 13,000 for greenhouse algae production. An integral part of this facility will be a pilot plant demonstration project using current closed system technology for economic assessment and optimization. To assist in the pilot plant design and operation, we have recently added to the research team a Ph.D chemical engineer and a master's level aquaculture engineer. This new engineering capability complements a very strong existing group of seven experienced principal investigators. Industry participation in the design, support and research activity of the pilot plant is being encouraged.

ANTICIPATED PROGRESS AND UNIQUENESS

Due to the outstanding progress made during the past year, particularly in the control of mass algal cultures, and to the strong interest expressed from industry in the closed system process, we expect to enter into a cooperative industry-University pilot effort to demonstrate the commercial feasibility of closed system bivalve mollusk culture before the end of the 1978-79 grant year.

RESUMEN

Durante miles de años el hombre ha practicado diversas formas de acuacultura, orientadas en su mayoría hacia el control de sistemas naturales. Sin embargo, la experiencia en la agricultura, que ha tenido la ventaja tecnológica de cientos de años, ha demostrado que ciertas cosechas (aves de corral, tomates de invierno, hongos, flores, etc.) se producen mejor en ambientes artificiales o con una gran supervisión. Aparentemente este es el caso de los moluscos bivalvos filtradores en Delaware.

Basados en el éxito de la propagación artificial de la agricultura, científicos de la Universidad de Delaware decidieron intentar producir moluscos marinos en un sistema artificial cerrado con un alto grado de control ambiental. El objetivo colectivo de esta investigación de maricultura es el de producir con algas y/o comidas preparadas, ostras y almejas nutritivas, de crecimiento rápido y de buen sabor, libres de toxinas y patógenos, en un sistema de agua salada con ambiente controlado, a un costo razonable, sin restricciones legales, usando fuentes naturales de energía y desechos orgánicos.

La introducción de nuevas cepas de mariscos y la explotación exitosa de las ya existentes puede proveer la base para establecer una nueva industria alimenticia marina costera. El programa de estudios marinos de la Universidad de Delaware se instituyó para desarrollar un prototipo de molusco para la adaptación industrial que fuera económica y tecnológicamente viable.

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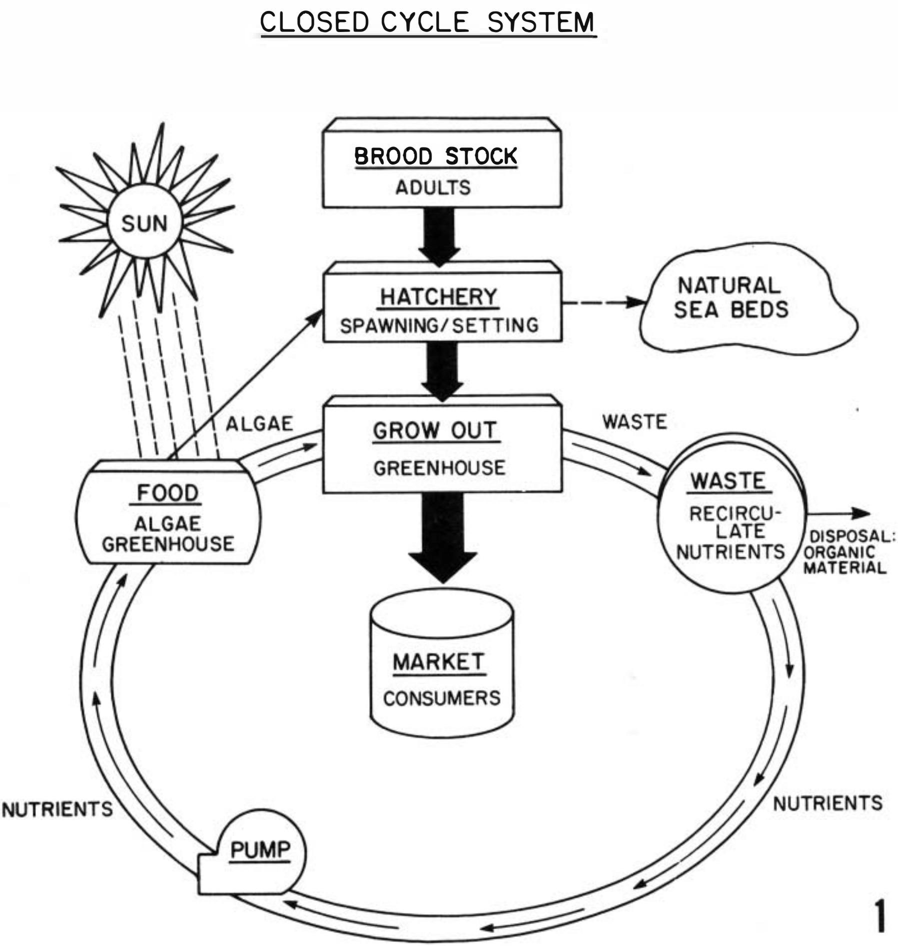
Fig. 1. Closed (Recirculated) System Concept


CLOSED CYCLE SYSTEM
BROOD STOCK
ADULTS
SUN
HATCHERY
SPAWNING/SETTING
NATURAL SEA BEDS
ALGAE
GROW OUT
GREENHOUSE
WASTE
FOOD
ALGAE GREENHOUSE
WASTE
RECIRCU-LATE NUTRIENTS
DISPOSAL: ORGANIC MATERIAL
MARKET
CONSUMERS
NUTRIENTS
PUMP
NUTRIENTS

1

Srna, E., C. E. Epifanio, M. Hartman, G. Pruder, & A. Stubbs
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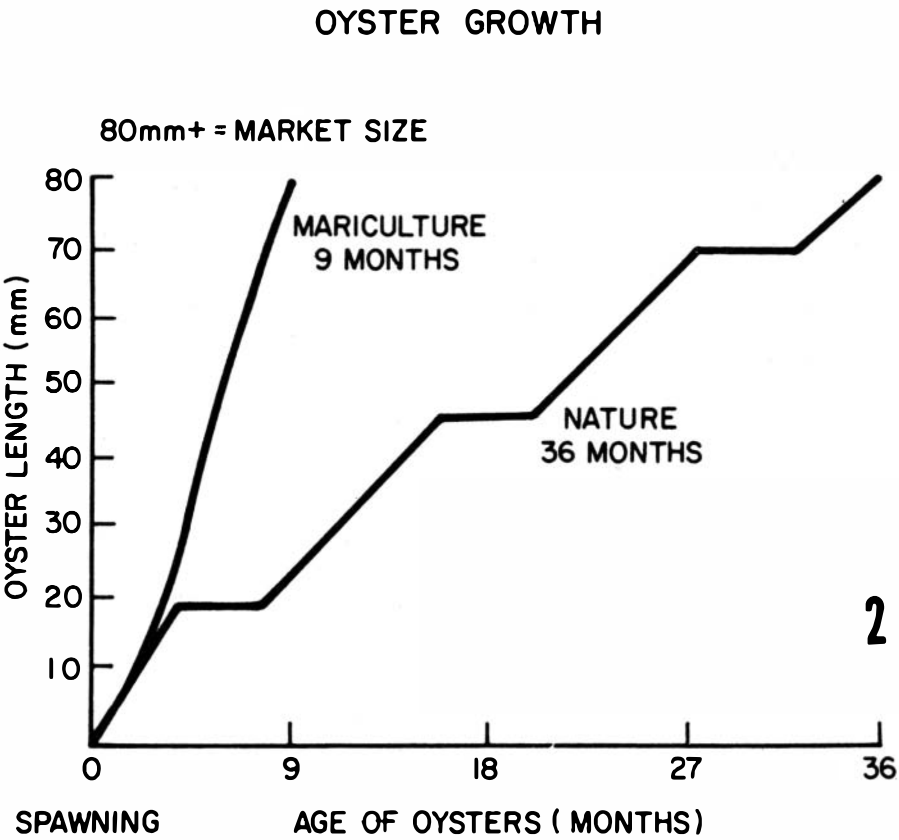
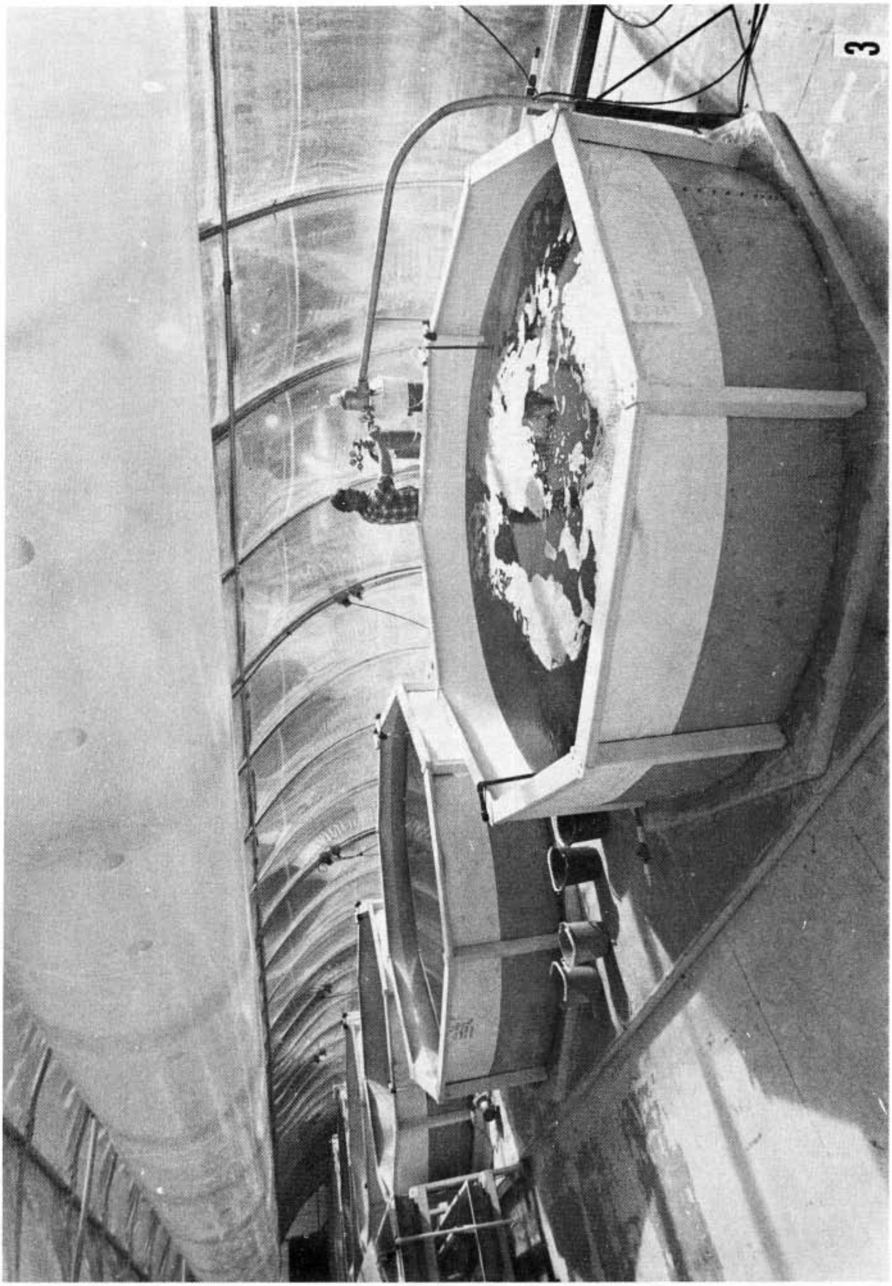
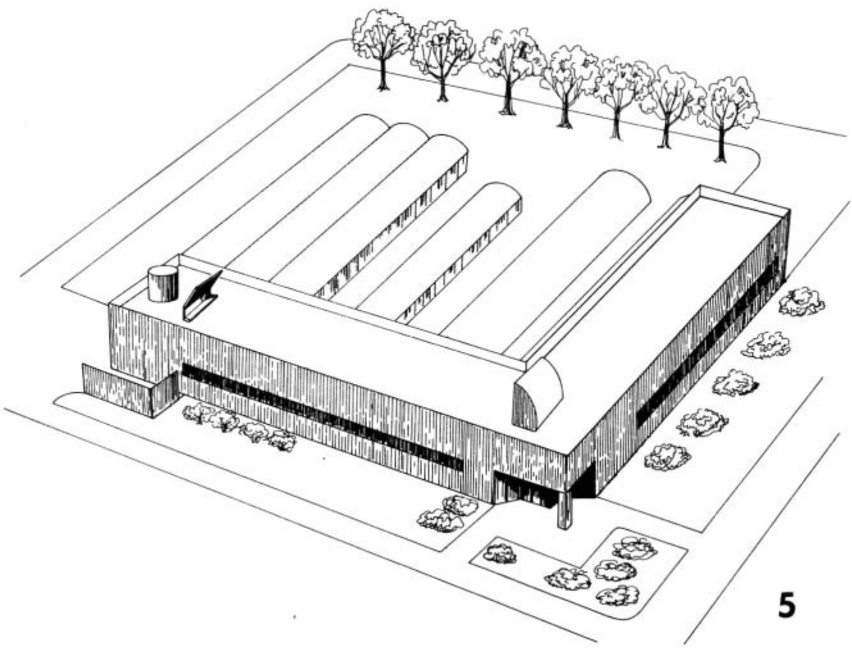
Fig. 2. A Comparison of Natural and Closed System Oyster Growth in Delaware

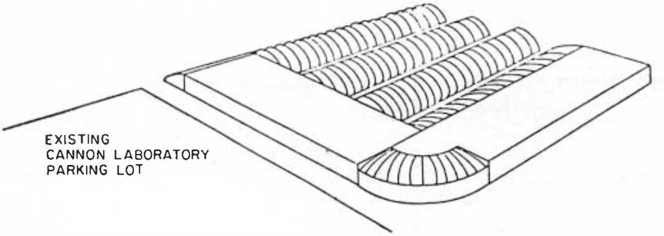

OYSTER GROWTH
80mm+ = MARKET SIZE
80
70
60
50
40
30
20
10
OYSTER LENGTH (mm)
MARICULTURE
9 MONTHS
NATURE
36 MONTHS
0
9
18
27
36
SPAWNING
AGE OF OYSTERS (MONTHS)
2


3



5

Fig. 5. Scale model of new $1.2 million mariculture laboratory currently under construction at the University of Delaware in Lewes, Delaware



PROPOSED CLOSED-SYSTEM
MARICULTURE RESEARCH LABORATORY

Marine Studies Complex
Lewes, Delaware