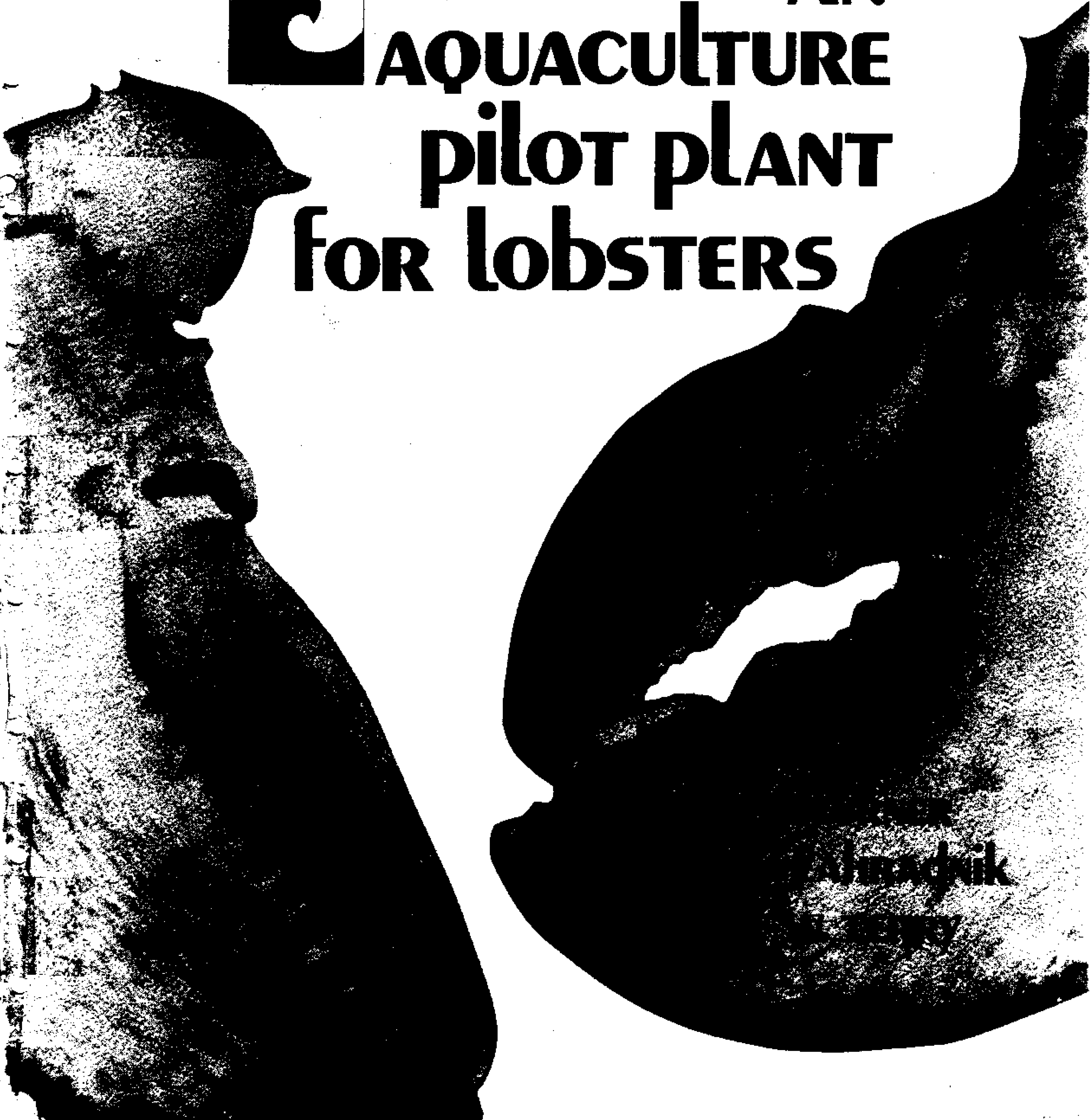
AN AQUACULTURE pilot plant for lobsters



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AN AQUACULTURE PILOT PLANT FOR LOBSTERS

by

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ACKNOWLEDGMENTS

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The authors also thank Paul Sarkisian for calculations on heat loss and solar input for alternative greenhouse materials.

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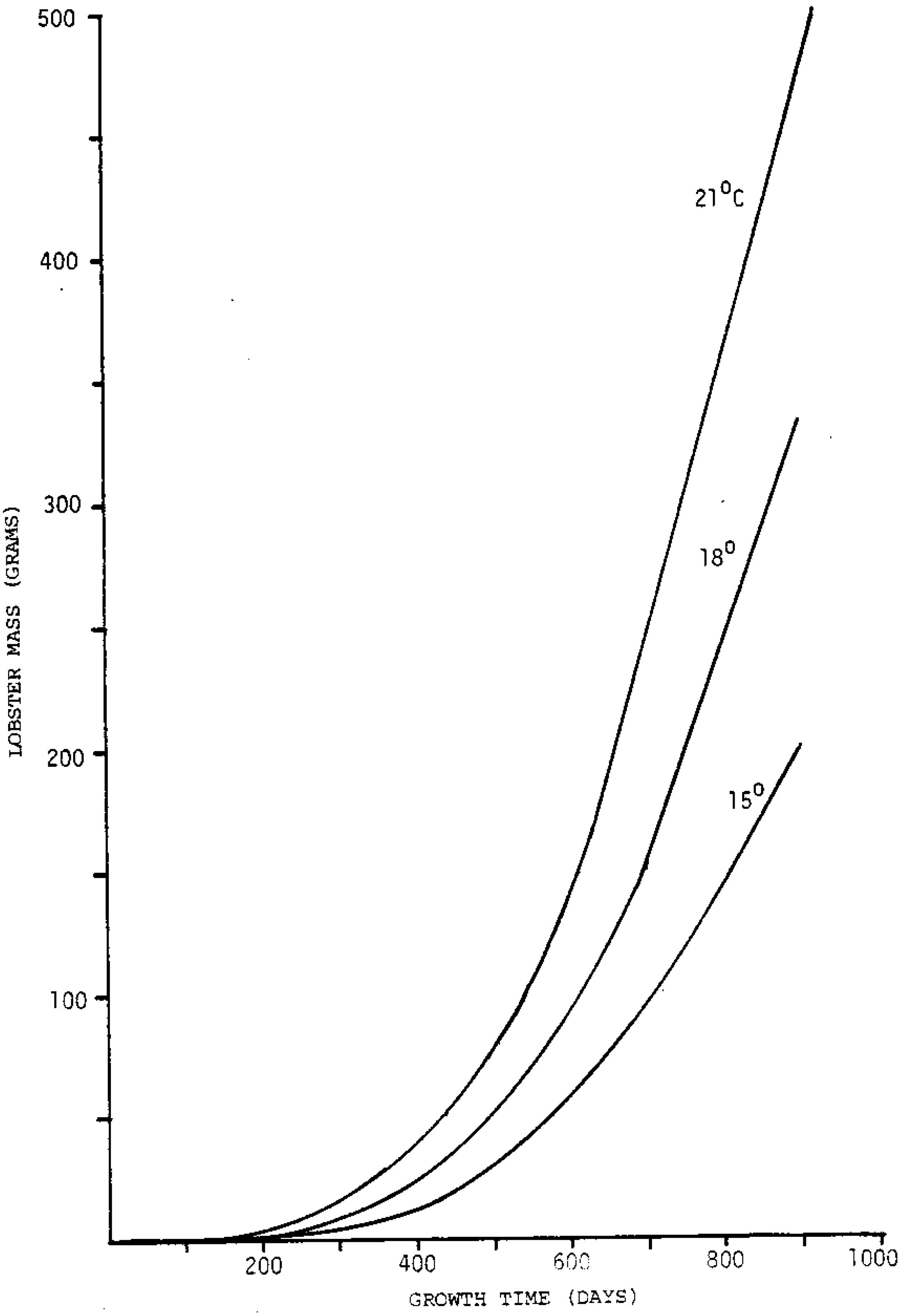
ABSTRACT

A major component of the proposed lobster-culture facility is heated waste water from a power plant. The warm water makes production feasible by speeding lobster maturation. This facility also cultures seaweeds that supply valuable products for food and pharmaceutical industries. Plans for the facility are described in detail.

The planned facility will help develop viable commercial aquaculture and demonstrate basic mariculture systems. Lobster culture appeals as a commercial venture because of high market value and large market potential, two factors essential to successful commercial aquaculture projects.

FIGURE 1 LOBSTER GROWTH AT CONSTANT TEMPERATURES



Source: Schuur, Allen, and Botsford 1974

INTRODUCTION--IMPROVING CULTURE

In the laboratory, scientists have successfully cultured many marine species from spawning to stocking and even to market size. Present aquaculture research focuses on improving culture technology to make commercial-scale production feasible.

A major drawback in mariculture (farming oceanic organisms) in temperate climates is that fish and shellfish typically require three to five years to reach market size. This slow growth ties up culture space, leads to low harvests, and leaves the cultured organisms prone to natural mortality, natural diseases, or culture system failure.

More rapid growth of cultured organisms may be attained by using the supply of heated water available from coastal electrical generating plants. A number of articles and experimental projects have addressed this possibility (Avon 1973; Boersma 1974; Kildow 1974; Lam 1974; Mathur 1970; Yarosh 1972). By maintaining elevated water temperatures during the winter, growth occurs year round and overall culture time may be cut in half (Figure 1). There is a potential for large-scale mariculture using the generous supply of heated water discharged from power-plant condensers.

To use waste heat for positive production is philosophically appealing--capitalizing on a previous environmental menace to produce much needed food. In practice, we must overcome many site-specific difficulties before production becomes commercially viable. Vanderborgh (1975) reports the successful use of power-plant effluent by Long Island oyster farms after modifications determined by on-site studies.

The present study focuses on an aquaculture pilot facility for the Shoreham Nuclear Plant of the Long Island Lighting Company. The design includes facilities to research aquaculture development problems. As our knowledge increases and feasible culture schemes emerge, the pilot plant could expand to commercial scale.

OBJECTIVE--ECONOMIC VIABILITY

This study analyzes a marine aquaculture complex to operate in conjunction with the Long Island Lighting Company (LILCO) nuclear power plant at Shoreham, New York. Personnel of the New York Sea Grant Institute, State University of New York, and LILCO would pursue research at the facility.

Before looking at a possible facility, let us consider trends in mariculture. The bulk of marine food harvest comes from fishing and gathering of wild stock. Rapid depletion of many prime species is leading to management practices aimed at maintaining a large enough wild population to produce a consistently high harvest.

To maintain high yields, the fisheries industry establishes quotas on yearly harvest, regulates fishing gear, and protects coastal nursery areas from pollution and urban development. These practices control man's devastation of resources but depend on the natural biological system in the seas. They do not improve upon nature.

Aquaculture aims to control predation and improve recruitment of desirable species. To control predators, hatchery stock is released when it is large enough to fend for itself; predators are eliminated within culture areas; or organisms are cultured outside the range of predators. Two practices may improve recruitment: augmenting the population with hatchery stock and protecting and improving natural spawning areas.

Improving recruitment introduces conflicting economic pressures. It is expensive to maintain hatchery stock in controlled,intensive systems. The expense increases in proportion to the animals' weight gain. However, the loss to predators drops radically as the size of the released stock increases. At the same time, there is always a risk of losing released organisms. Private enterprise needs assurance that a significant harvest will offset the expenses of hatching and rearing. This requires control and monitoring of released stock, difficult under natural conditions.

The uncertainties of natural biological and physical elements in open water, the problems of pollution, legal competition for navigation rights, and the public use of waterways all direct establishment of aquaculture in controlled cages, ponds, or tanks. In the distant future, closed-system culture from spawn to harvest may become a reality.

The long-term objective is to establish an economically viable commercial mariculture operation. However, it is not possible to complete a detailed design for the long term due to our limited ability to predict future developments. At best, the proposed facility should be flexible enough to allow alteration and expansion to commercial operation. For the present, the facility meets requirements for laboratory and pilot-plant scale experimentation on basic mariculture. The facility is large enough to permit significantly large-scale investigations of problems in using thermal effluent for aquaculture.

Pilot-plant scale developmental projects are extremely important because most mariculture concepts have not been proven. Extrapolating data from well-controlled laboratory experiments to commercial scale ignores many cost and control problems. Although insufficient economic incentive discourages private industry from financing demonstration projects, pilot plants are needed to develop basic mariculture concepts and study numerous problems.

Early in this project, we decided to gear the facility to specific projects, rather than to marine research in general. The primary emphasis is on Homarus americanus, the American lobster. The design of the facility is adequate for culture of many species. The choice of a particular lobster species does not limit system flexibility, but specifies a tangible project goal.

We decided to design the facility to support a yearly culture of 5000 lobsters. Operating the facility will provide experience with physical systems and actual production procedures.

FIGURE 2 MAJOR INPUTS AND OUTPUTS FOR THE PROPOSED AQUACULTURE FACILITY

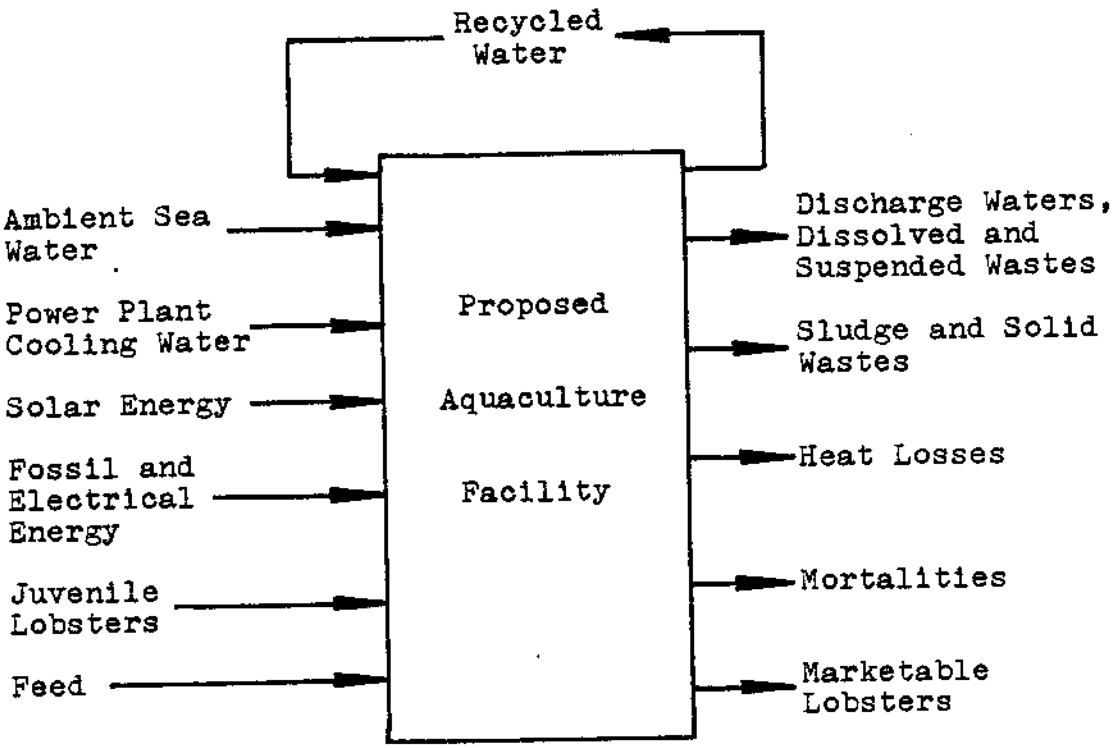


FIGURE 3   LOBSTER SIZE INCREASE PER MOULT

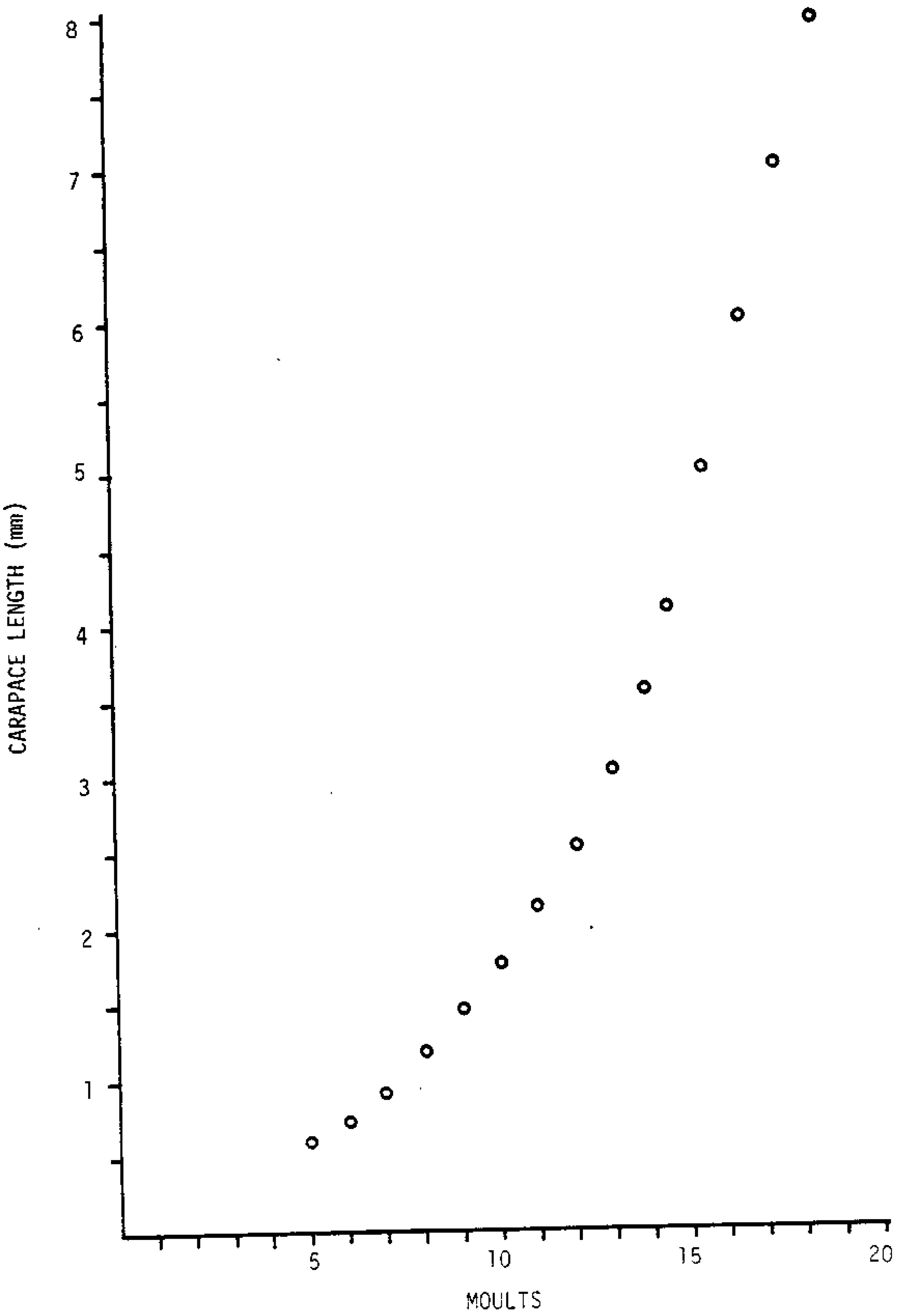
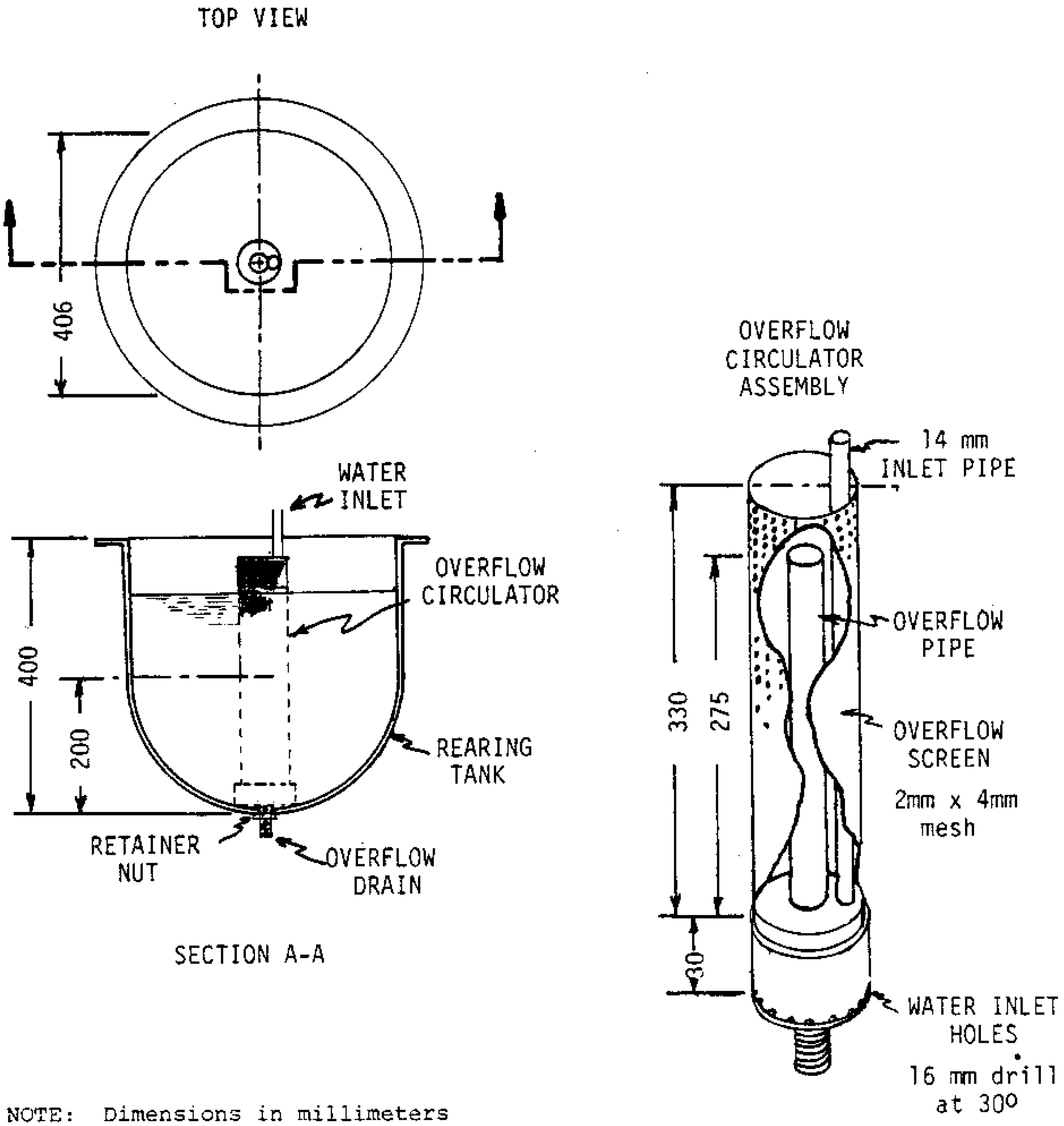


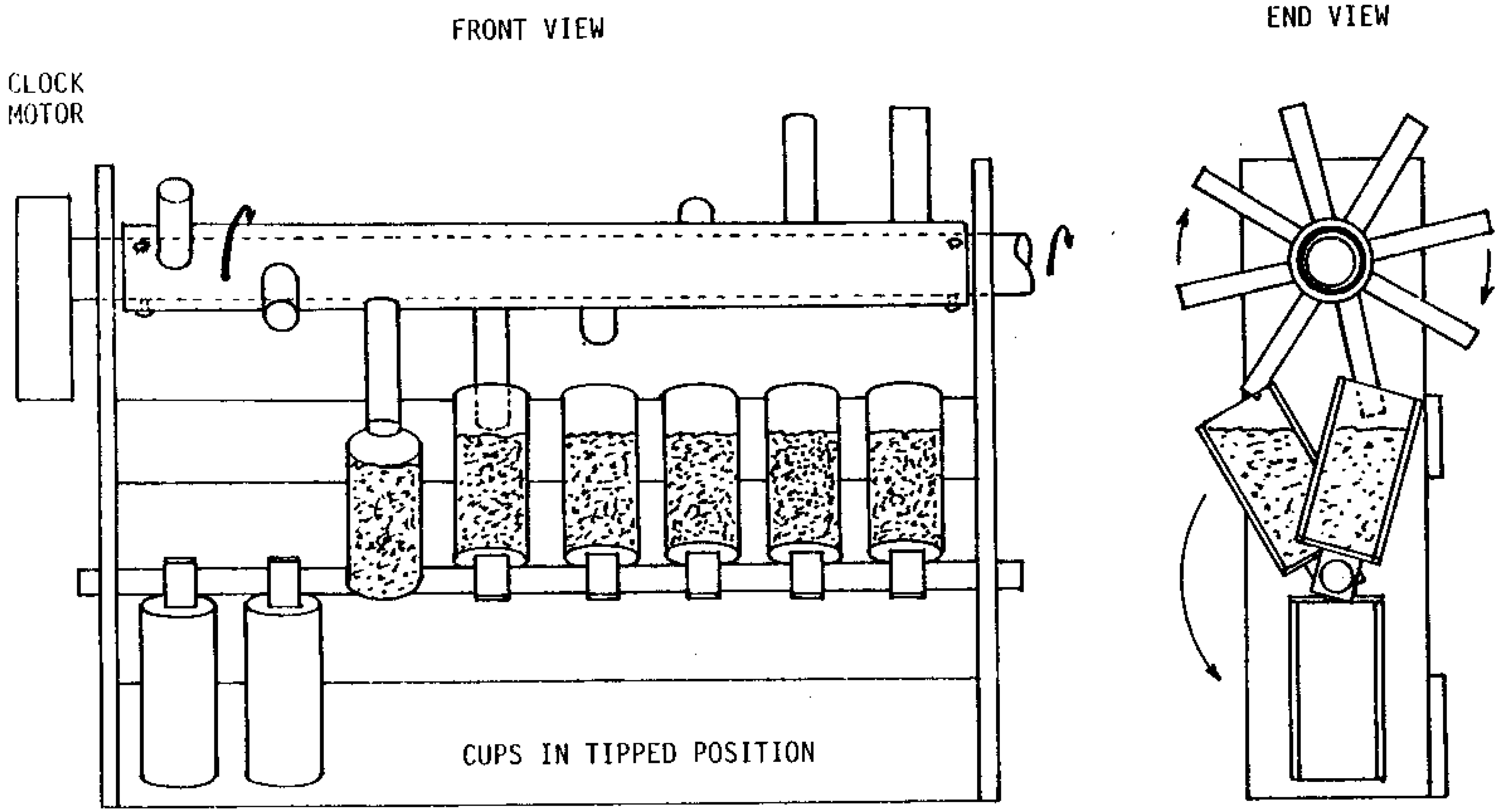
FIGURE 4 HUGHES LARVAE-REARING TANK



NOTE: Dimensions in millimeters

Source: Hughes et al. 1974

FIGURE 5 AUTOMATIC FEEDING UNIT

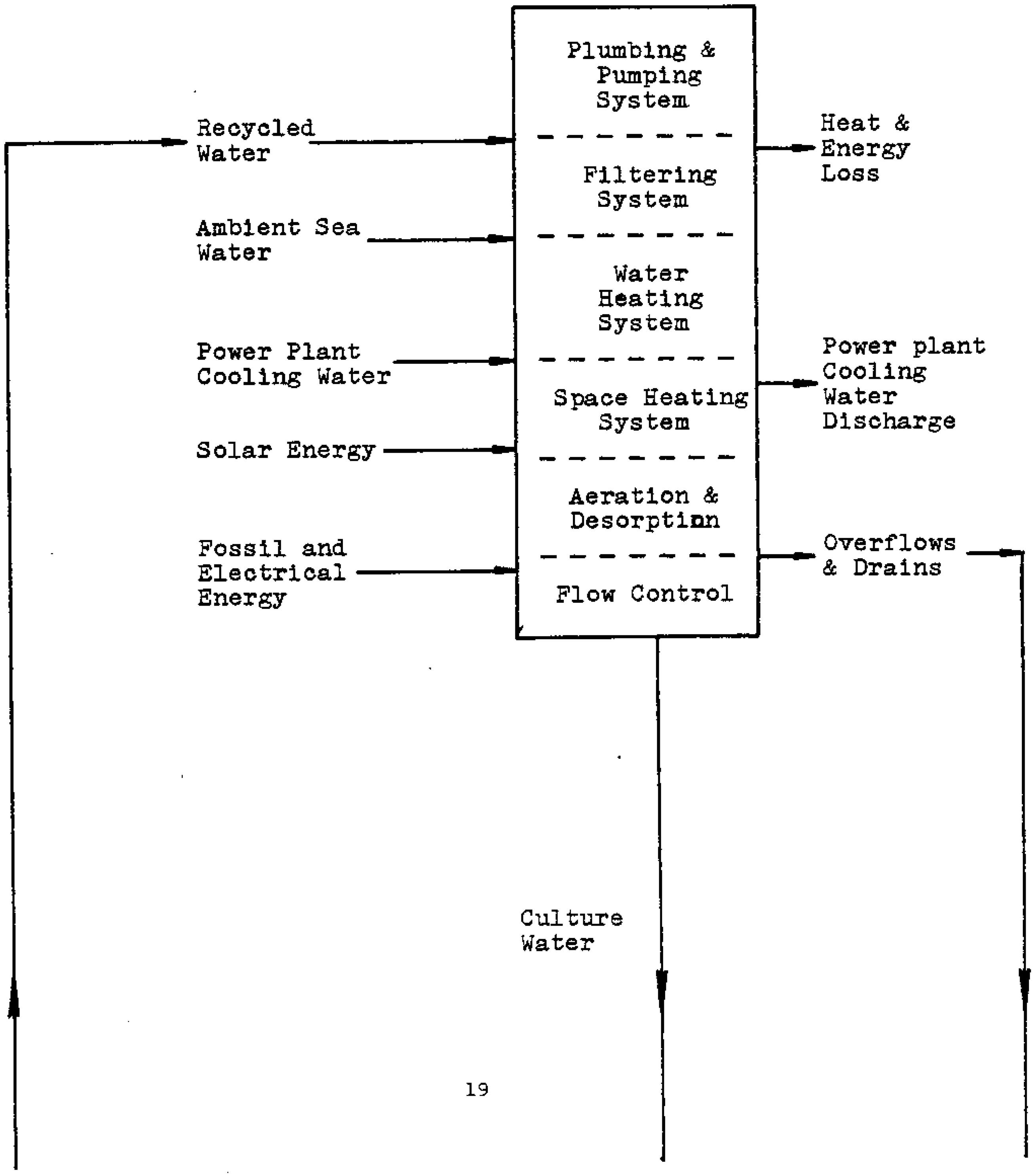


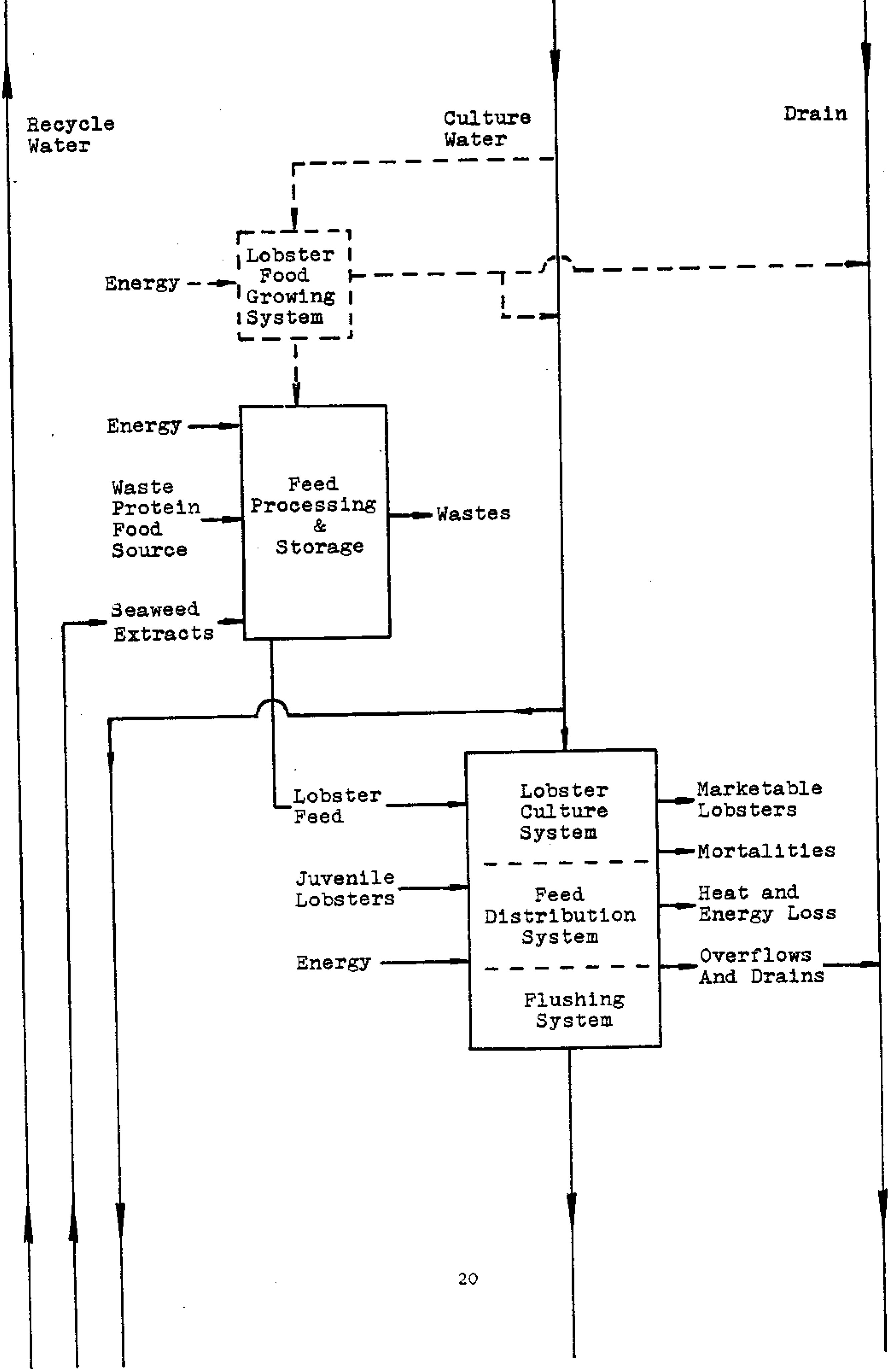
FRONT VIEW

END VIEW

Source: Serfling, Van Olst, and Ford 1974

FIGURE 6 MAJOR SUBSYSTEMS FOR THE PROPOSED AQUACULTURE FACILITY




Recycle Water
Culture Water
Drain
Energy
Lobster Food Growing System
Energy
Waste Protein Food Source
Feed Processing & Storage
Wastes
Seaweed Extracts
Lobster Feed
Juvenile Lobsters
Energy
Lobster Culture System
Feed Distribution System
Flushing System
Marketable Lobsters
Mortalities
Heat and Energy Loss
Overflows And Drains

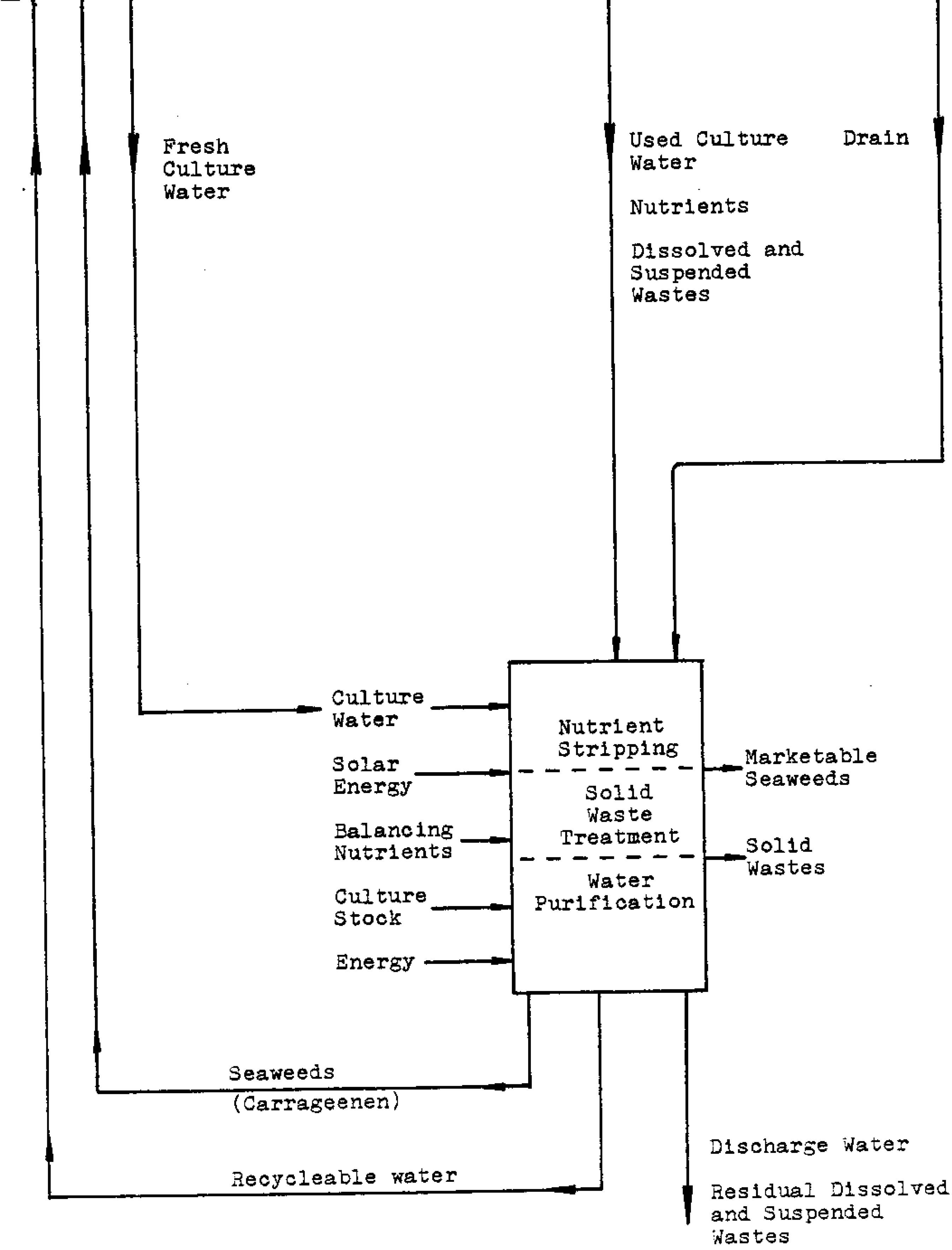
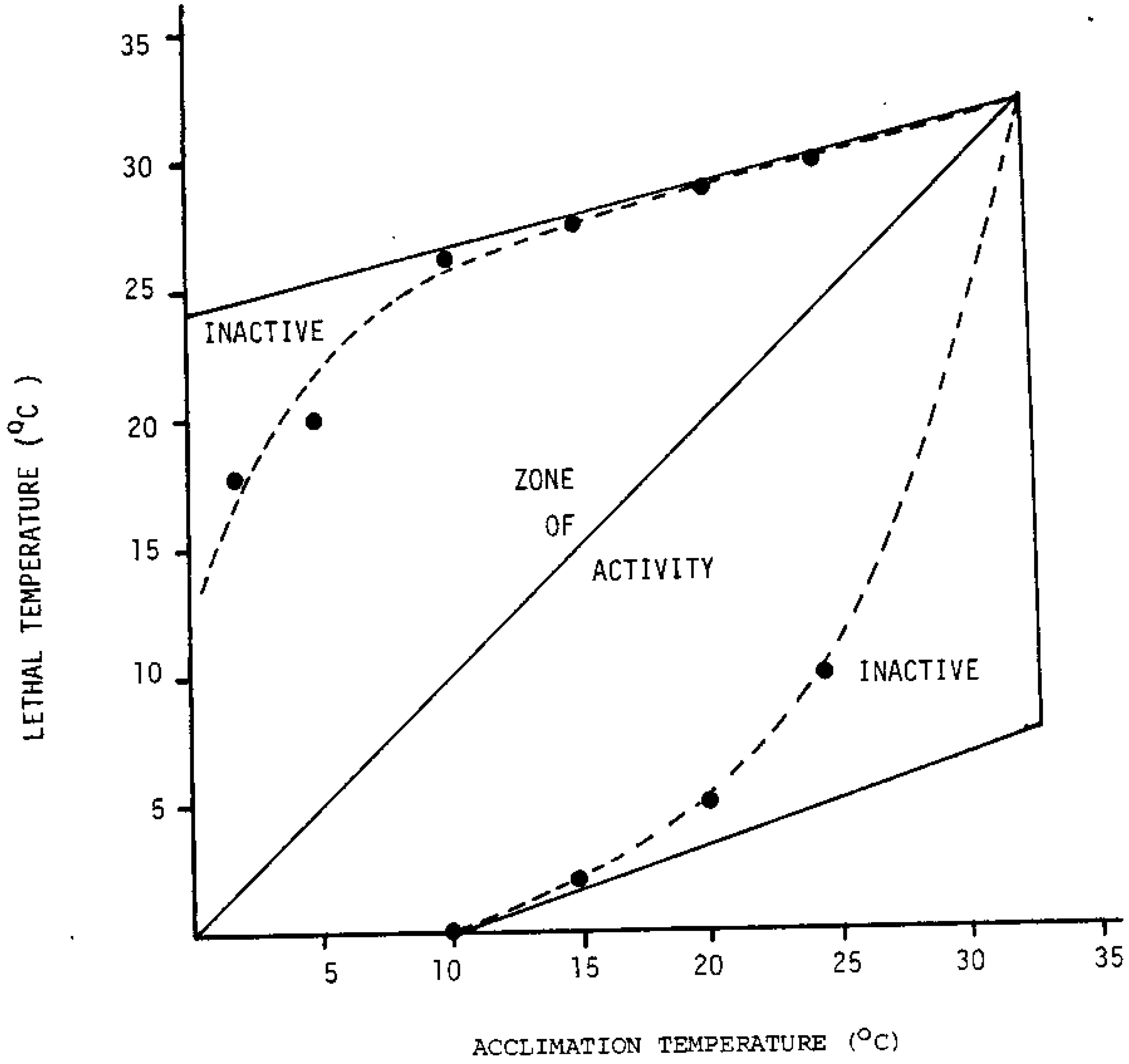

Fresh Culture Water
Used Culture Water
Nutrients
Dissolved and Suspended Wastes
Drain
Culture Water
Solar Energy
Balancing Nutrients
Culture Stock
Energy
Nutrient Stripping
Solid Waste Treatment
Water Purification
Marketable Seaweeds
Solid Wastes
Seaweeds
(Carrageenen)
Recycleable water
Discharge Water
Residual Dissolved and Suspended Wastes

FIGURE 7 EFFECT OF TEMPERATURE SHOCK ON LOBSTERS



Source: McLeese and Wilder 1958

FIGURE 8 AMBIENT AND EFFLUENT SEA WATER TEMPERATURE (SHOREHAM, L.I.)

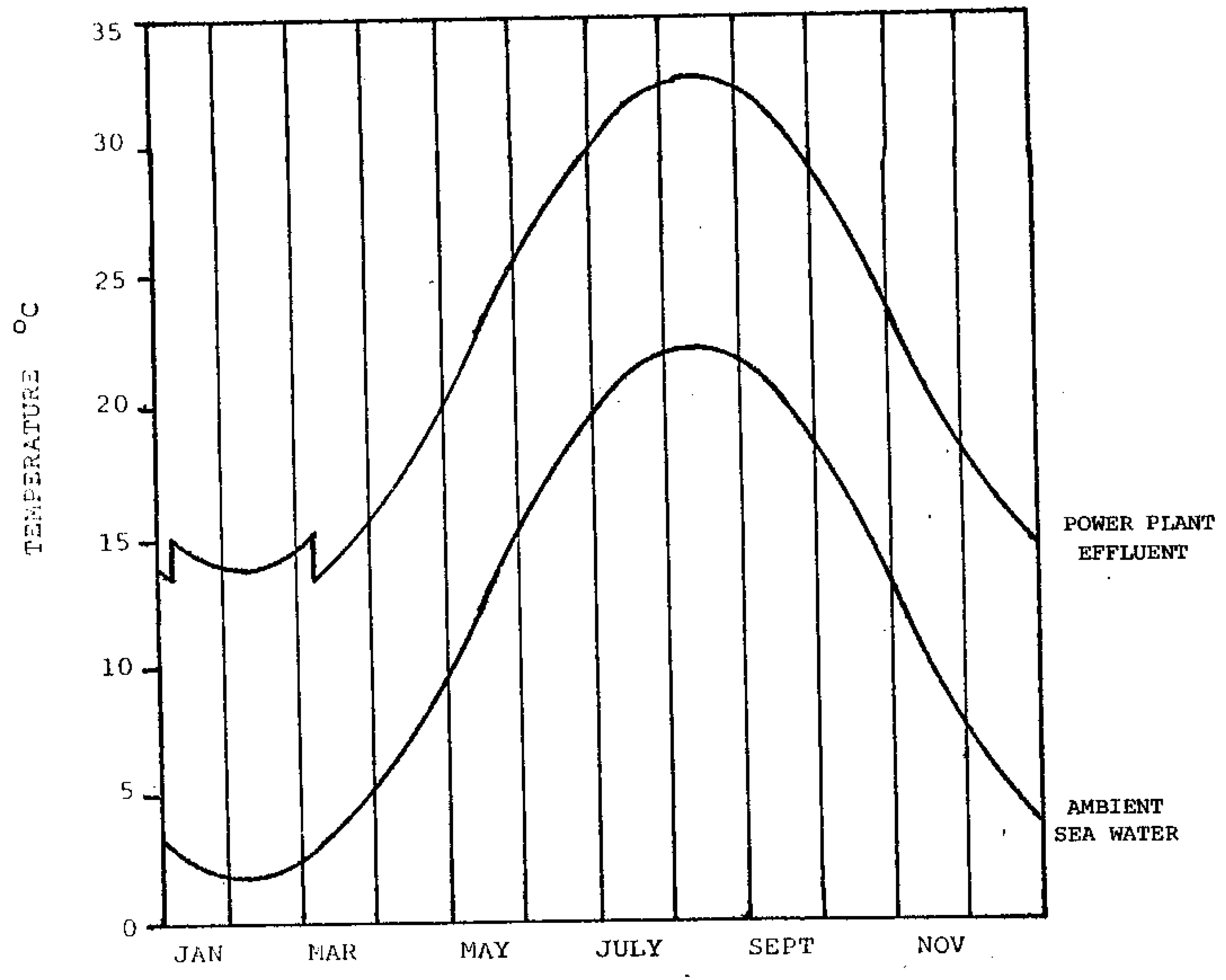


FIGURE 9 COMMUNAL BOTTOM LOBSTER CULTURE

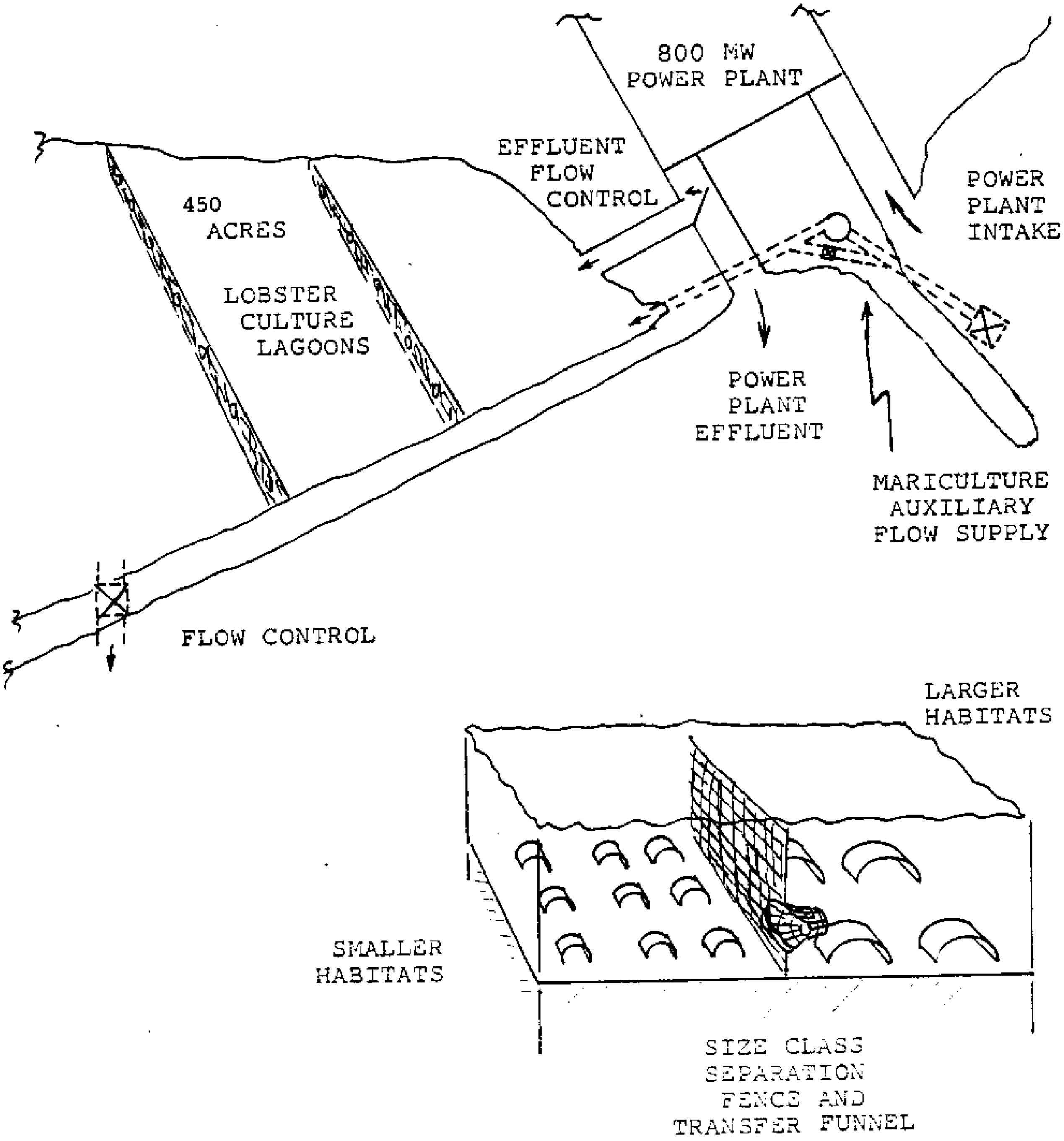


FIGURE 10 STACKED-TRAY RACEWAY LOBSTER CULTURE

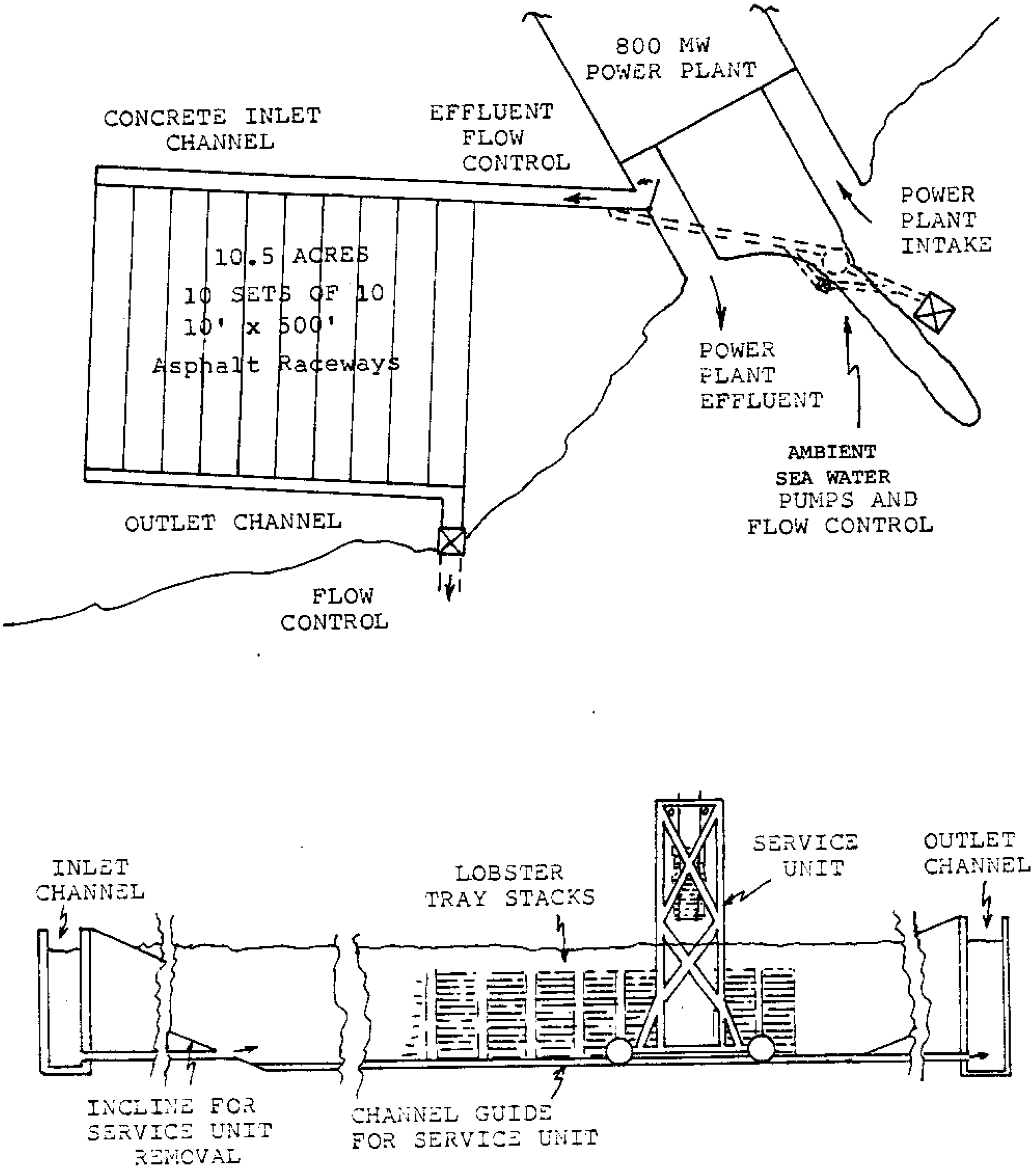
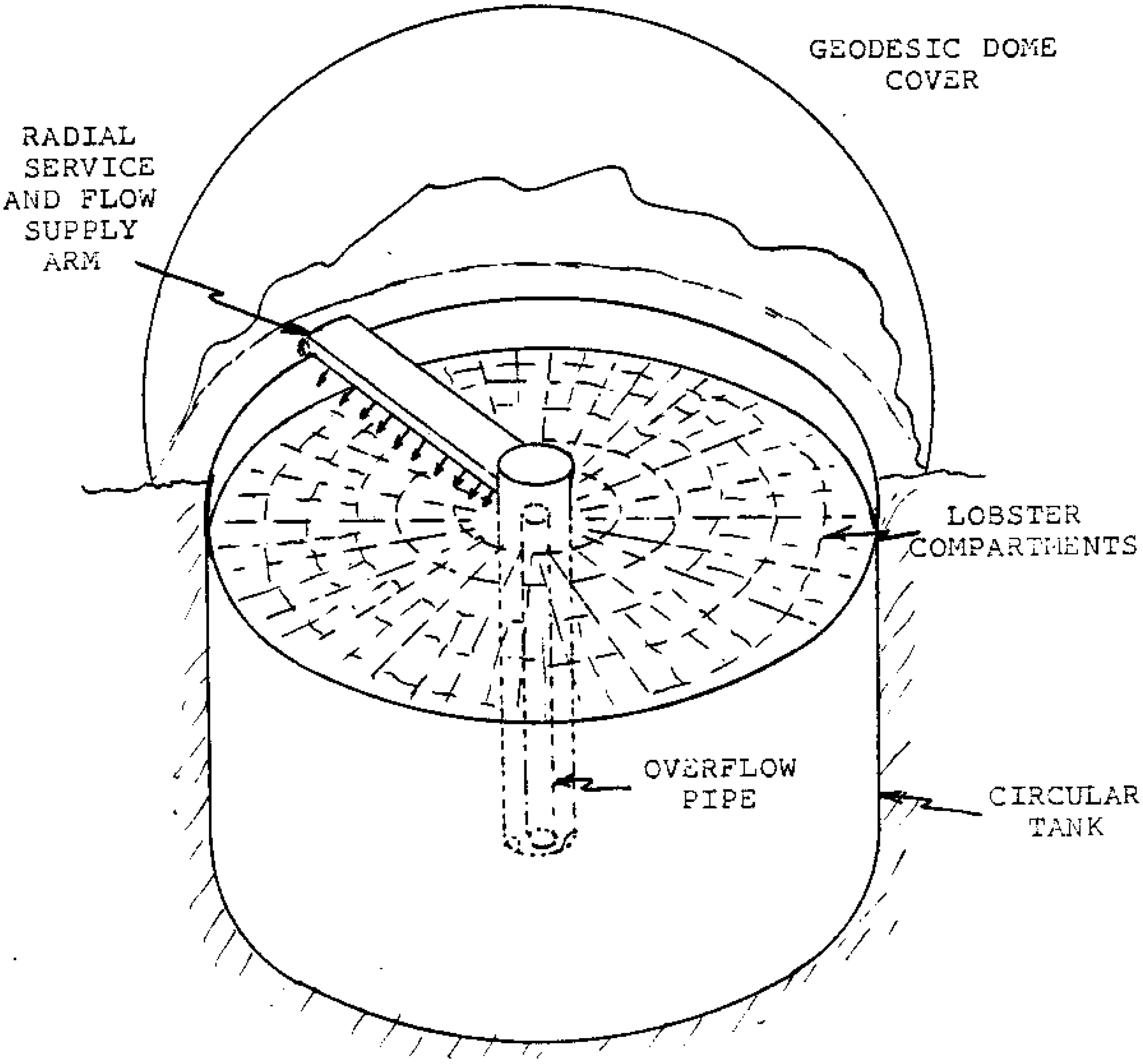
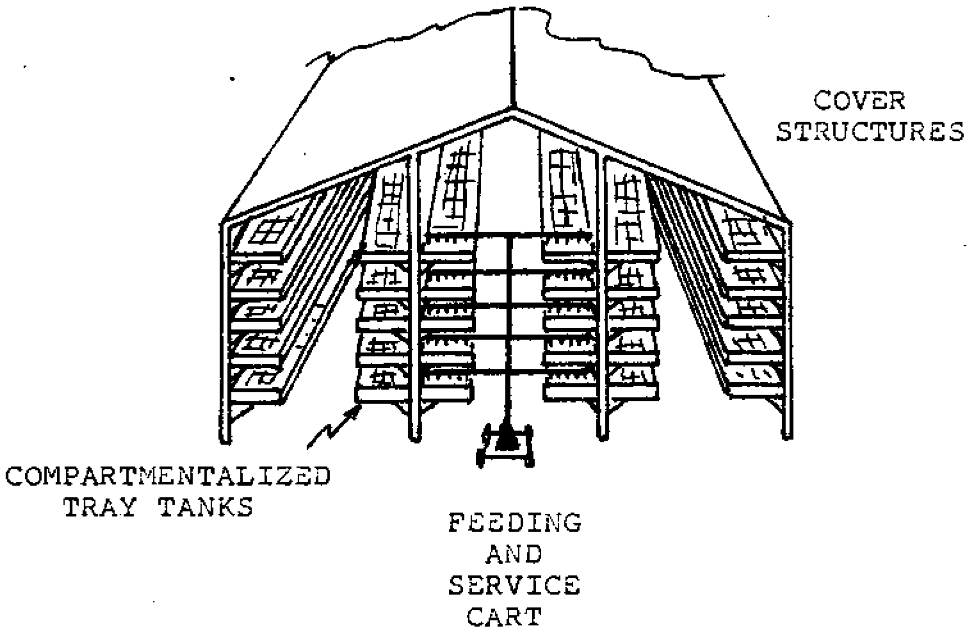


FIGURE 11 CIRCULAR LOBSTER CULTURE



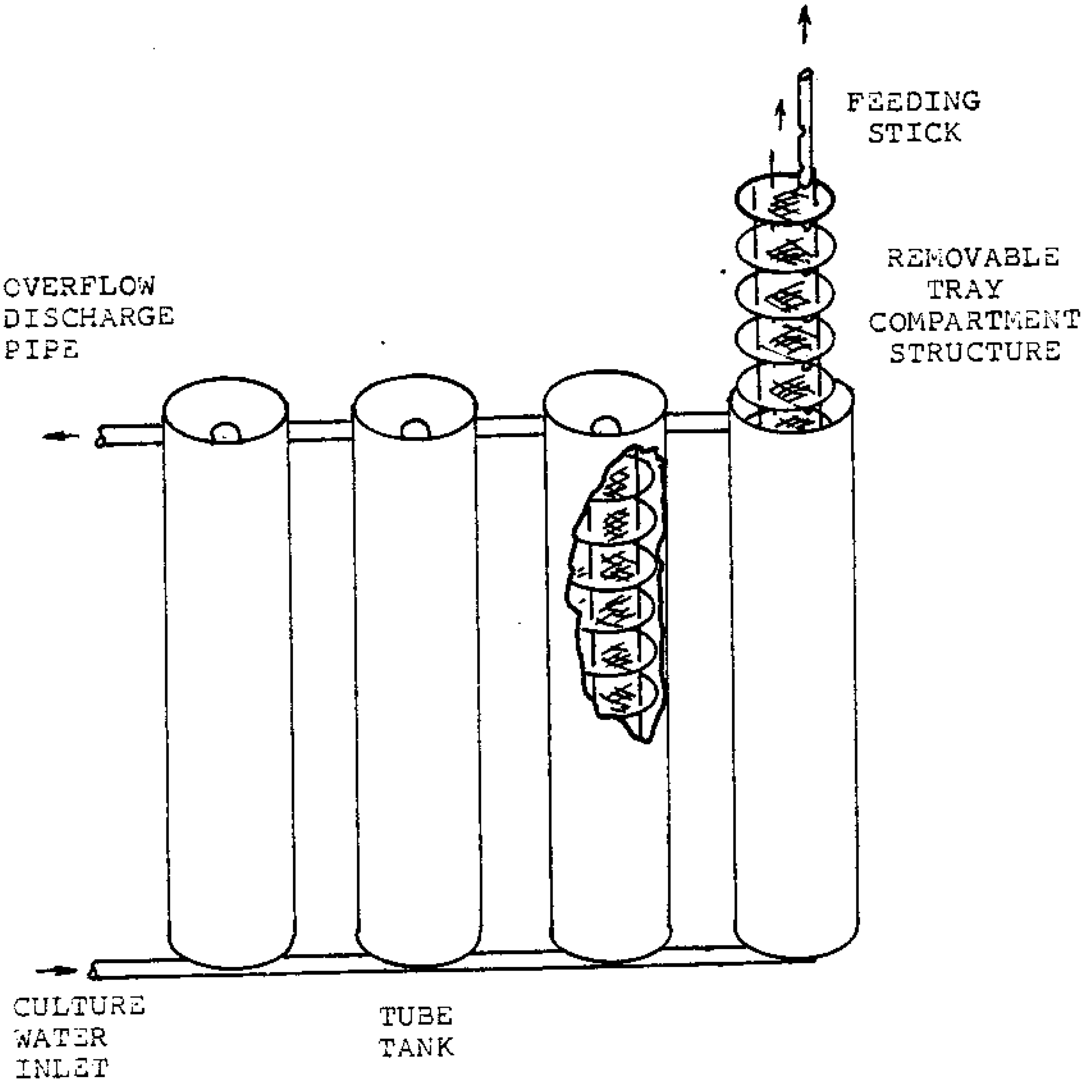
Source: Van Olst and Carlberg 1975

FIGURE 12 STACKED-TANK CULTURE FOR JUVENILES



Source: Van Olst and Carlberg 1975

FIGURE 13 TUBE CULTURE FOR JUVENILES



ALTERNATIVE CULTURE SYSTEM DESIGNS

The mariculture complex design includes laboratory facilities for biological research and design options. The facility has a sea-water laboratory, a dry laboratory, and office space. The laboratories are supplied with fresh water, sea water, and electricity. An outdoor test pad with a suitable water supply will accommodate small pilot studies. This pad will not have built-in tanks.

However, to raise 5000 lobsters a year, the pilot plant must have built-in tanks, plumbing, and support facilities. Since basic structures will be relatively inflexible, we need to investigate several different, potentially viable culture schemes to design the most feasible plant.

Figure 2 illustrates the major inputs and outputs of a lobster-culture plant. The power plant's thermal effluent is of primary interest because the ability to capitalize on this heat source determines the profit potential of the entire power-plant mariculture scheme. The desired goal is marketable lobsters.

Expected Losses

Figure 2 shows the system losses and disposal problems. Mortalities and heat losses, capital and operating costs, and culture requirements must be considered to determine permissible loss levels. If the power plant's thermal effluent can be converted to cheap, hot culture water, the overall cost of heat decreases. Likewise, to minimize operational costs and maintain a steady growth rate, the mariculture system must foster a low mortality rate. It is difficult to estimate the effects of system design and operation on mortality. Studies at the facility are necessary to determine these factors. The pilot plant must dispose of sludge, solid waste, and waste water in accordance with Environmental Protection Agency (EPA) regulations. Discharge of heated waste water may be a major economic loss if water heating costs are high.

Trace levels of radioactive elements exist in effluent from nuclear power plants (Table 1). Food and Drug Administration (FDA) regulations currently prohibit direct use of nuclear-plant effluent for culturing food. In addition, toxic levels of chlorine are used in cleaning power-plant

TABLE 1 *Anticipated annual release of radioactive material in liquid effluent from Shoreham Nuclear Power Station (100% power)*

Nuclide	*Curies/year	Nuclide	Curies/year
$^{89}\mathrm{Sr}$	0.45	$^{132}\mathrm{I}$	0.042
$^{90}\mathrm{Sr}$	0.029	$^{133}\mathrm{I}$	0.14
$^{91}\mathrm{Sr}$	0.00044	$^{135}\mathrm{I}$	0.00013
$^{90}\mathrm{Y}$	0.10	$^{134}\mathrm{Cs}$	0.25
$^{91m}\mathrm{Y}$	0.028	$^{136}\mathrm{Cs}$	0.073
$^{91}\mathrm{Y}$	0.22	$^{137}\mathrm{Cs}$	0.19
$^{93}\mathrm{Y}$	0.0044	$^{137m}\mathrm{Ba}$	0.036
$^{95}\mathrm{Zr}$	0.0047	$^{140}\mathrm{Ba}$	0.65
$^{97}\mathrm{Zr}$	0.0000079	$^{140}\mathrm{La}$	0.5
$^{95}\mathrm{Nb}$	0.0048	$^{141}\mathrm{Ce}$	0.0050
$^{97m}\mathrm{Nb}$	0.000076	$^{143}\mathrm{Ce}$	0.00055
$^{97}\mathrm{Nb}$	0.0000079	$^{144}\mathrm{Ce}$	0.0032
$^{99}\mathrm{Mo}$	0.095	$^{143}\mathrm{Pr}$	0.0040
$^{99m}\mathrm{Tc}$	0.091	$^{144}\mathrm{Pr}$	0.0032
$^{103}\mathrm{Ru}$	0.0034	$^{147}\mathrm{Nd}$	0.0016
$^{106}\mathrm{Ru}$	0.0011	$^{51}\mathrm{Cr}$	0.040
$^{103m}\mathrm{Rh}$	0.0034	$^{54}\mathrm{Mn}$	0.0035
$^{105}\mathrm{Rh}$	0.00033	$^{55}\mathrm{Fe}$	0.18
$^{106}\mathrm{Rh}$	0.0011	$^{59}\mathrm{Fe}$	0.0066
$^{127m}\mathrm{Te}$	0.00097	$^{58}\mathrm{Co}$	0.42
$^{127}\mathrm{Te}$	0.0010	$^{60}\mathrm{Co}$	0.044
$^{129m}\mathrm{Te}$	0.0091	$^{65}\mathrm{Zn}$	0.000088
$^{129}\mathrm{Te}$	0.0058	$^{69m}\mathrm{Zn}$	0.000021
$^{131m}\mathrm{Te}$	0.0010	$^{187}\mathrm{W}$	0.016
$^{131}\mathrm{Te}$	0.00019	$^{24}\mathrm{Na}$	0.0021
$^{132}\mathrm{Te}$	0.040	$^{32}\mathrm{P}$	0.0015
$^{130}\mathrm{I}$	0.000096		
$^{131}\mathrm{I}$	1.2	Total	$\sim$ 5 Ci
		H_3	$\sim$20 Ci

* A Curie is 3.7×10^{10} disintegrations per second.

condensers (Table 2). The proposed plant must have uncontaminated, ambient sea water for culture. The flow rate of culture water depends on the needs of the organisms cultured, the amount of water recycled, and the efficiency of the water purification system.

TABLE 2 *Discharges from the Shoreham plant*

Parameter	Average intake concentration (mg/l)	Average discharge concentration (mg/l)
Boron[1]	4.6	4.601
Soldium[2]	7200	7200.1
Sulfate[2]	1780	1781
Chlorine[3]	<.1	.2
Suspended solids[4]	5	30
Oil and grease[4]	1	10

[1] Discharged once a month
[2] Discharged once every 10 days
[3] Discharged 2 hours/day; 9 months/year
[4] Average values allowed by US EPA. Not discharged into cooling water system.

Power-plant shut downs or inadequate heat transfer from the power-plant effluent to the culture water may require alternate energy sources--solar energy, electricity, or fossil fuels--to maintain culture temperature. This is particularly important for research purposes. Additional solar energy may be needed for the photosynthesis in waste-water treatment, for purifying recycled water, and for culturing algae for lobster feed. Additional electrical and fossil fuel will be needed for water pumps, water treatment systems, and lighting.

The Lobster Life Cycle

The lobster life cycle stretches over several years, but only a few of the 5,000 to 125,000 eggs released by the female reach maturity. Copulation occurs within 12 days after the female moults (Bardach et al. 1972; Gates et al. 1974; Hughes 1973). The female stores the sperm for 9 to 13 months. When she spawns, the eggs leave her body through genital openings and, after fertilization, stick to nonplumose hairs of the lobster's foot-like swimmerets. Incubation takes 10 to 12 months, until the water temperature reaches 15 to 20°C (59-68°F) in mid-May, when hatching occurs. Together, mating and hatching normally take two years, but keeping water temperature at 20°C (68°F) can reduce this time to 11 months.

Off the coast of Massachusetts, lobster maturation, through numerous moults, normally takes five to seven years. Figure 3 shows size increase per moult for juvenile stages. At a constant temperature of 15.6°C (60°F), lobsters moult twice as often as they do in ambient New England waters. Hughes reports that it is possible to produce marketable lobsters in two years at 20 to 23°C (68-73°F). He reports that, in selected cases, lobsters reached market size in 18 months.

SHORTENING THE LOBSTER LIFE CYCLE

From the variability of the lobster life cycle it is clear that there is the potential to shorten the normal process and improve the economic feasibility of commercial culture.

The Hughes larvae-rearing tank (Figure 4) fosters greater survival of newly hatched lobsters, which usually survive at a rate of 0.1 percent at the fourth stage of development, the stage at which swimming larvae become bottom-crawling lobsters. The system of rearing larvae is fairly well developed. However, engineering improvements for reducing maintenance requirements in large facilities undoubtedly are impossible. For example, Figure 5 shows an automatic feeding unit which permits unmanned, scheduled feeding of the larvae. A hatchery and feed-processing facility on site are desirable options for the pilot plant.

Lobster survival depends on a low incidence of disease. The high-density growing conditions that exist in intensive lobster aquaculture lead to rapid spread of diseases, such as gaffkemia (red tail), and shell infections.

To keep disease bacteria from building up in culture water, tanks must not contain stagnant pockets (Gates et al. 1974). The system should provide adequate circulation, water flow, and removal of stale food and organic deposits.

Using many culture units with isolated flow systems and removing sick animals minimize the chance of disease spreading throughout the entire facility (Rauch et al.). Low temperatures and starvation, or minimal feeding, may reduce the infection rate if an epidemic appears imminent.

MAJOR SUBSYSTEMS

Within the pilot facility, several subsystems control an intensive culture process. Figure 6 shows a more detailed diagram of the energy and mass flow between the major subsystems of an intensive lobster-culture facility. Major systems are:

1. culture water supply and treatment;
2. feed processing and storage;
3. lobster culture; and
4. water treatment for recycle or discharge.

Three sources of culture water are ambient sea water, plant cooling effluent, and recycled water from the mariculture facility. An intensive culture facility should filter incoming water to 55 micrometers to reduce both seston and fouling organisms. Aerating heated water eliminates supersaturation. Supersaturating the water with air, particularly nitrogen, causes a gas disease in lobsters similar to the bends. Supersaturation may occur when saturated water is heated or when air leaks on the vacuum side of the pumps. It is possible to eliminate supersaturation by having a large air-water interface, by agitating the water, or by bubbling air through a column of water.

Water and space heating systems ideally derive most of their energy from the power plant's thermal effluent. In the event of a power-plant shut down, the lobster facility will need auxiliary heat to cover critical needs and avoid excessive temperature shock (Table 3). Figure 7 illustrates the effect of temperature shock on lobsters. The heating and plumbing system must not inflict excessive temperature change on lobsters.

TABLE 3 *Design information*

Power plant output (full load): 820 MW

Planned shut down: 30 days/year

Operational experience of other nuclear plants:

	% time on line	% load
High	89	77
Average	71	68
Low	45	38

Temperature transients in diffuser pipe:

Full load start up	18°F in 2 hrs.
Full load shut down	14°F in 4 sec.
Backwash	5.4°F in 1 min.

Design cooling water temperature increase:

Normal operation	19.7°F
January and February	23.1°F

Cooling water and discharge pipe:

Flow rate	590000 GPM
Filtration	3/8 inch
Pipe diameter	12 feet
Pipe wall	12-inch concrete
Discharge pressure at recirculation pipe	7 PSIG
Elevation at recirculation pipe	8 feet
Elevation at beach fence	4 feet

Other site data:

Area of site	3 acres
Maximum high tide	11 feet
Ground water level	5 feet

Freezer space must accommodate several weeks supply of feed. Measuring and blending equipment are needed to mix feed ration. And cooking facilities are necessary to prepare low-quality waste protein, likely to be poorly maintained before reaching the facility. Feed must be prepared in a form suitable for measured distribution to the lobsters.

The lobster culture system must accommodate water and feed distribution, routine inspection and transfer of lobsters, and cleaning and flushing. These factors vary with the type of culture system and the size of the lobsters.

The waste water from the lobster culture contains dissolved nutrients and particulate material. The level of dissolved nutrients should be less than that of the secondary effluent discharged from sewage treatment plants. Under normal continuous operation, the culture waste water is not a major pollution threat because it is still high enough quality to at least marginally support lobsters. Flushing and cleaning the culture system generates large sediment loads which a clarifier or sedimentation pond removes before discharge.

Since power-plant effluent is below optimum growth temperature during mid-winter months (Figure 8), fossil or electrical energy can provide heat for culture water. The energy required for even a moderate temperature increase is high. Recycling heated culture water permits optimum culture temperature with less energy input. A biological filter of dolomite and gravel is the most proven solution for nutrient removal and pH maintenance in recycled water. The air supply in the biological filter maintains suitable levels of dissolved gases.

Seaweed nutrient stripping,which may be used prior to, or in place of, the biological filter,produces a useful by-product of the recycling system. While culture methods for seaweed are not well established, seaweed's commerical value for food and pharmaceutical products surpasses that of the lobsters. Other water treatment options include foam fractionation, carbon filters, chlorination, and ozonation, but all are experimental or costly at this time.

Lobster Culture Systems

The design of commercial lobster-culture systems requires consideration of the following factors:

- Capital costs
- Operating costs for physical plant maintenance
- Heating
  - Heat loss
  - Culture water heating
  - Space heating
- Feed cost
- Lobster maintenance
  - Physical structures
  - Feed distribution
  - Inspection
  - Removal of dead
  - Stocking and transfers
- Water quality maintenance
  - Water flow
  - Circulation
  - Culture volume
  - Cleaning
  - Air supply
- Lobster growth rate
  - Feed quality
  - Space
  - Water quality and temperature
  - Intraspecific interactions
- Mortality
  - Cannibalism
  - Injury
  - Disease
  - Predation
- Harvesting

The relative importance of each of these factors varies greatly for different culture schemes. Figures 9 through 13 outline several potential culture schemes.

BOTTOM CULTURE

Figure 9 presents a culture system with a natural bay or man-made lagoon using power-plant thermal discharge. Fencing the inlet and discharge points confines the lobsters and keeps out predators and food robbers. Habitat and size separation limit cannibalism. One-way transfer funnels between size groups aid natural size sorting by allowing transfer to larger culture areas and habitats as the lobsters grow. Fouling problems and the inability to eliminate small predators make the system unsafe for juveniles.

There is a lack of design information on communal housing for larger lobsters. Large ponds, not tanks, are necessary. These offer several advantages:

1. on a per area basis, it is cheaper to construct ponds than tanks with individual compartments;

2. scattering food evenly over the pond eliminates the need for placing measured amounts in each lobster compartment;

3. fresh and recirculated waters create larger circulation patterns; and

4. large, communal culture systems could use the direct flow of power-plant cooling water into a pond or fenced area in a discharge plume.

The disadvantages of pond use include the following:

1. the system needs a large area per animal;

2. shelters or habitats are necessary;

3. cannibalism is a problem (low-temperature acclimation to communal living and sufficient feeding rates with high calcium food reduce this);

4. removal of stale food and wastes is difficult;

5. higher flows of new or treated recirculated water may be required due to No. 4 above and effects of sediment accumulation on water quality; and

6. inspection of the animals, removal of unhealthy lobsters, and isolation of lobsters during moulting are more difficult.

Such communal bottom culture requires large areas. Proper stocking density and flow requirements are largely unknown. Table 4 assumes that proper distribution of habitats, adequate feeding, and size separation will permit densities of .15 kilogram per square meter (.031 lbs/ft^2), twice that observed by Sheehy (1976). The inability to clean the system and the unknown effects of sediments and benthic communities on water quality necessitate a flow of 8 liters per minute per kilogram (.96 gal/min/lb) of lobster biomass. Because of large surface area and flow requirements, auxiliary heating and recirculation systems are not viable in this system. Feed requirements also are unknown. Inefficient flow circulation, feed distribution, and unavoidable benthic and small swimming organisms in the

TABLE 4 *Projected communal lobster culture parameters*

A) Individual lobster requirements

Lobster age (days)	150	300	450	600	750	900
Carapace length (mm)	14	27	41	54	68	81
Mass (g)	1.7	15	53	135	280	508
Area (m2)	.011	.10	.35	.90	1.9	3.4
Flow (l/min)	.014	.12	.42	1.1	2.2	4.1
Feed (g/day)	.26	1.6	4.6	10.2	18.8	31.5
No. lobsters/lobsters marketed (20% overall survival)	1.53	1.30	1.18	1.10	1.04	1.00

B) Requirements per 500g-lobster marketed per year

Lobster age (days)	300	600	900	Total
Max. biomass (g)	19.5	149	508	676
Max. feeding (g/day)	2.08	11.2	31.5	44.8
Total feed (kg)				10.5
Area (m^2)	.13	.99	3.4	4.5
Max. flow (l/min)	.16	1.2	4.1	5.4
Effective tidal flow (l/min) (1.7m tide range)				9.8

system reduce efficient food use. Table 4 assumes twice the feed requirements of individual compartment cultures listed in Table 5.

Under the stated assumptions, an 800-megawatt plant using a cooling-water flow of 2.2 million liters per minute (590,000 gal/min) supports an annual 400,000-lobster operation on 1.82 square kilometers (450 acres) of culture area. To avoid excessive cost, a location requiring only minor construction for the culture system is necessary. Such a plant would not maintain maximum lobster growth rate. Winter effluent temperature is below optimum and would cool an additional 6°C (42.8°F) before discharge. Because effluent temperature in the summer is too high for culture, it is necessary to eliminate power-plant flow and provide ambient water exchange. Power-plant flow would also have to be diverted during periods of heavy chemical discharge. Indeed, the whole scheme as portrayed becomes useless if persistant trace levels of chemicals and radioactive elements cannot be cleared with the FDA.

TABLE 5 *Projected requirements for lobsters cultured in individual compartments*

A) Individual lobster requirements

Lobster age (days)	-14	0	150	300	450	600	750	900
Carapace length (mm)	-	-	14	27	41	54	68	81
Mass (g)	-	-	1.7	15	53	135	280	508
Area (m^2)	-	-	.0029	.011	.025	.044	.069	.098
Volume (l)	-	-	.12	.89	3.1	7.1	14.	24.
Flow (l/min)	-	-	.0014	.012	.044	.11	.23	.42
Feed (g/day)	-	-	.13	.80	2.3	5.1	9.4	16.
No. lobsters/lobster marketed (40% overall survival)	8.3	2.5	1.3	1.2	1.1	1.06	1.02	1.00

B) Requirements per 500g-lobster marketed per year

Lobster age (days)	300	600	900	Total
Max. biomass (g)	18.0	143	508	669
Max. feeding (g/day)	.96	5.4	16.	22.
Total feed (kg)	-	-	-	5.16
Area (m^2)	.013	.047	.098	.16
Volume (l)	1.07	7.53	24.0	32.6
Max. flow (l/min)	.014	.12	.42	.84
Effective tidal flow (l/min)	-	-	-	.35
(Stacks 10 trays deep in 1.7m tide range)				
Min. summer pumping (l/min)	-	-	-	.49

Assuming a 1.7-m (5.6-ft) tidal range and suitable circulation in the culture area, tidal exchange could supply a more than sufficient ambient water flow. The culture lagoon exit would be closed during incoming tides. Gravity aided flow through the ambient supply system or power-plant condensers would decrease pump energy requirements.

The factors mentioned previously--unpredictable biological responses, pollutants, low control of the culture, and site-specific construction details--make general production and cost estimates useless at this time. Despite these factors, communal bottom culture warrants further investigation because of its easy maintenance and applicability to large-scale operations.

Because the Shoreham power plant uses a diffuser pipe for cooling water discharge, the site is not geographically suitable for creating large culture lagoons. Therefore, the planned facility does not emphasize communal bottom culture. Seaweed-culture ponds, included in the design, may be modified to permit pilot-scale study of bottom culture.

RACEWAY CULTURE

Using individual compartments for rearing lobsters takes less area and eliminates cannibalism. These advantages might offset the disadvantages of individual feeding, individual transfers, and high-quality environment required for the dense culture. Figure 10 illustrates a raceway system which features stacked, compartmentalized trays for high-density culture in thermal effluent. This system requires construction of special culture raceways, trays, and handling equipment. Table 2 summarizes system parameters. The raceway system assumes 40 percent survival from fourth stage (0 days) to market. This survival rate is higher than that for communal culture. Improved control and water quality maintenance of the system permit lower flow.

An 800-megawatt power plant with a cooling-water discharge of 2.2 million liters per minute (590,000 gal/min) can nurture 2.7 million lobsters per year in a 42,492-square meter (10.5-acre)culture area with trays stacked 10 deep. The area requirement is much lower than that for bottom cultures, and the stacked-tray raceway system conveniently adapts to a greater number of sites. Maximum temperature loss in the system is less than .5°C (.9°F) during winter months.

Tidal exchange provides a maximum of 42 percent of the summer flow requirements for ambient water, necessitating a supply of pumped water. By preventing culture discharge during imcoming tide, a subtidal pump bypass pipe could provide 70 percent of the required steady-state flow of 2.2 million liters per minute (590,000 gal/min). An increased flow of 3.2 million liters per minute (845,000 gal/min) could be pumped as the tide recedes to make up for flow deficiency during tidal input. Inexactness of design information makes it unclear whether this cyclical flow supply is biologically feasible or economically justifiable. As energy costs increase, any practical tidal pumping system warrants serious consideration.

Two other problems are inherent in the sea-level raceway system.

1) Flow at high tide may bypass the lobster culture trays through the unobstructed flow area above the stacks. 2) Gravity cannot drain the system, thereby hindering thorough cleaning and complicating raceway construction and repair.

Cost Analysis

Operating costs for feeding and maintaining the lobsters are difficult to assess. The cost analysis in Table 6 assumes that, in addition to preparing the feed and maintaining the physical plant, 100 workers can feed and care for all the lobsters. For service units, the system uses elevator carts that travel the length of the raceways in concrete tracks. There are a number of ways to distribute feed to the lobsters--tray by tray,through feed tubes, or in paste form on feeding sticks.

The cost analysis in Table 6 outlines the estimates of major capital and operating expenses. Estimates suggest that a break-even operation could run about $1.68 market price per 500-gram (1.1-lb) lobster. A profit margin of 20 percent requires a price of $2.05 per lobster.

These figures are not exact. Reliable operating methods and cost estimates require several years of testing. Also, biological responses are not completely predictable; pollutant effects have been ignored; and winter power-plant shut downs are not included.

ALTERNATIVE TANK CULTURE

Water quality and cleaning ease are uncertain factors in the culture scheme in Figure 10. Figure 11 presents a scheme suggested by Van Olst et al. (1975). The circular tank and angled water jets on the radial service arm maintain a vortex in the tank which draws sediment to the central drain.

The advantage of the circular tank in water quality maintenance is clear--system maintenance decreases significantly. However, the construction cost and inefficient space use do not appear as favorable to commercial-scale systems as the raceway system.

Individual compartment design also is complicated. Compartments are either nonuniform in size and shape, which complicates mass production, or they are uniform in size but irregularly spaced on the radius. For these reasons this study does not further analyze circular tank systems.

TABLE 6 *Cost estimates for subtidal stacked-tray lobster culture* (2.7 x 10^6 lobsters/year; 820-megawatt power plant)

A) Capital costs

Land	$ 100,000
Earth removal and grading	200,000
Raceway construction	1,700,000
Pumps, plumbing and controls	1,000,000
Culture trays	600,000
10 Feeding and service units	700,000
Feed storage freezers	200,000
Administration building	100,000
Vehicles	200,000
Contingency	200,000
TOTAL	$5,000,000

B) Annual operating costs

Feed at $100/mg	1,350,000
Juveniles (Table 4)	337,500
Electricity	50,000
2 Administrators at $25,000	50,000
4 Professionals at $20,000	80,000
100 Workers at $10,000	1,000,000
Maintenance	500,000
Contingency	500,000
TOTAL	$3,867,500

C) Cost benefit estimate

Gross annual income	
2.7 x 10^6 lobsters at $1.80	4,860,000
Annual expenses	
Operating costs	3,867,500
Interest and capital payments (at 8.5% for 20 yrs.)	675,000
	$4,542,500
Profit estimate (6.35% of capital)	$ 317,500

JUVENILE CULTURE

The stacked-tray raceway system is appropriate for culturing larger animals. However, fouling and feed distribution difficulties seriously limit its effectiveness for juvenile culture in small compartments with small flow openings. Figure 12 illustrates a system of stacked tanks for culturing small animals. Tanks could be equipped with perforated compartments or coarse aggregate (such as whole oyster shell) to provide habitats for communal culture. In either case, periodic flushing would clean the tanks and a multi-armed service cart would feed the lobsters. The small space requirement for juveniles reduces capital cost. Single layers of animals in the tank ease inspection, transfer, and maintenance.

Juvenile fourth- and fifth-stage lobsters can grow through several moults in communal tanks with adequate food and shelter to reduce cannibalism. Miller (1975) reports that,in San Diego, tanks lined with unbroken oyster shells provided adequate survival. He does not suggest stocking densities. Berrill et al. (1972) show that young lobsters burrow under 3- to 6-centimeter (1.2-to 2.4-in) rocks or shells into firm mud to provide their own shelter. Fourth-stage lobsters, about 11.9 millimeters (.47 in) total length, dig U-shaped tunnels 3 centimeters (1.2 in) deep, with 5 centimeters (2.0 in) between each opening. Eighth-stage lobsters, about 23 millimeters (.91 in) total length, dig tunnels about 9 centimeters (3.5 in) deep and 12 centimeters (4.7 in) long. Again, appropriate stocking density is unknown. Problems in removing wastes and unused feed could arise with a mud substrate.

Each container needs adequate water flow and circulation to maintain proper water quality. Tanks and compartments generally are made of plastic or fiberglass. Habitats made of short lengths of standard-diameter plastic pipes and vacuum-molded polyethylene tanks provide an inexpensive, long-lasting culture system (Schuur et al. 1974).

To date, most researchers place lobsters in individual growth chambers at the fourth or fifth stage. Suggested chamber dimensions are five by three times the carapace dimensions with a depth that is one to three times the carapace length. But many investigators use cubes or cylinders of comparable volume.

Lobsters are moved to progressively larger compartments as they grow. The compartments have a screen bottom in tanks which can be flushed to remove metabolic waste, sediments, and unused food particles.

In Figure 13 juveniles are cultured in vertical tubes equipped with removable, perforated tray structures. Feeding and maintenance are highly efficient and accurately controlled. Resulting low maintenance cost and high culture efficiency offset the relatively high cost of the culture structures and flow distribution system (Cobb 1976).

Diet and Maintenance

Conversion ratios of feed to lobster weight as low as fifteen to one have been reported. Obviously the nutritional content of the feed must be satisfactory for the lobsters to grow to marketable size. Live brine shrimp is the best feed for culturing lobsters, with a conversion of only four to one (wet weight). They are, however, an expensive feed for lobsters.

Gates et al. (1974) report that high-calcium diets reduce cannibalism. A whole shrimp and whole soft-shell clam diet, though expensive, meets the high calcium requirement. Another successful diet is a prepared food of spiny lobster carapace, squid, ulva, and Enteromorpha with 50 percent solids and 50 percent water. The gelatinous seaweeds in this mixture bind the feed. This feed has several advantages: it may be frozen for storage, does not cause fouling, and is rich in vitamins. A food made from fish flour, fish meal, and cat food, using a seaweed carrageen gel base also has proven successful.

Miller (1975) reports best results from diets of ground-up lobster or lobster combined with brine shrimp. Obviously these are expensive. A diet of trout pellets produces underdeveloped lobsters; trout pellets, however, mixed with red crab or some other marine organism, produce healthier lobsters.

Hughes (1973) reports the successful use of a mixture of shellfish, shellfish viscera, and fish for lobster feed. Cat and dog food containing fish meal, meat meal, soy bean meal, milk products, and cereals also are acceptable.

Conclusions drawn from Castell's study (1974) are that lobsters may require up to 60 percent protein for rapid growth, and trace amounts of a host of vitamins and minerals promote health and proper caste development. Lobster feed should contain high calcium content for shell development and reduction in cannibalism. Castell (1975) found that juvenile lobsters in particular need .5 percent cholesterol for proper growth.

It seems wise to use whole, natural sources in lobster feed to supply vitamins and trace minerals. Besides nutritional requirements, the feed must satisfy other criteria:

- it must be acceptable to the lobsters;
- it must not dissolve or crumble;
- it must be storable;
- it must be compatible with the mechanics of portioning and distributing feed;
- it must be removable if uneaten within 24 hours after feeding; and
- it must be inexpensive.

Feeding Rates and Schedules

Nearly all authors recommend daily feeding for lobsters grown in water above 15°C (59°F). One weekly feeding suffices in the winter. Below 5°C (41°F), lobsters usually stop eating.

Hughes et al. (1972) report 4-to-1 conversions of feed to animal weight in warm water and 11-to-1 conversions in cold water. A similar range of conversions exists in warm water, depending on the type of feed used. Feed range from 3 to 5 percent of the animal weight per day. The rate obviously depends on the quality of the feed, the water temperature, the growth rates of the cultured lobster strain, and waste which may occur due to the feeding scheme or compartment design.

Stewart et al. (1972) report that unfed 500- to 600-gram (1.1- to 1.3-lb) lobsters remain healthy for 95 days at 5°C (41°F), 32 days at 10°C (50°F), and 11 days at 15°C (59°F).

Schuur et al. (1974) present the following equation for feeding rate as a function of animal weight:

$$\frac{dF}{dt} = k_f w^n$$

where $n = 0.84$

$k_f = 0.03$

w = animal weight in grams

F = food weight in grams

t = feeding frequency in days

This represents a conversion of about 2.5 to 1 with $k_f = 0.03$, assuming that a 500-gram (1.1-lb) lobster can be produced in 900 days. It is unlikely that any commercial operation could attain this conversion. Even a conversion ratio of 4 to 1 appears to be overly optimistic with the present state of the art. The value of k_f may be set realistically to 0.0118 times the expected conversion. Thus for a feeding operation in which the expected conversion ratio is 8 to 1, the value for k_f is 0.0826. Maintaining this conversion ratio results in a feeding plan of 4.4 percent of the animal weight per day at 50 grams (.11 lb), and 3 percent at 500 grams (1.1 lb).

Survival

Despite extreme care in water conditioning, feeding, cleaning, and disease prevention, some lobsters inevitably die. Schuur et al. (1974) suggest an equation to formulate 60 percent survival from juvenile to marketable size (900 days):

$$\%\ \text{survival} = (t + 1)^{-0.0721} \times 100$$

where t is time in days. This equation has not been tested in large-scale practice. Because a commercial facility cannot afford the same individual attention given in experimental investigations, this study uses a modification of the equation. It allows for 40 percent survival after 900 days:

$$\%\ \text{survival} = (t + 1)^{-0.135} \times 100.$$

Space Requirements

Gates et al. (1974) propose a minimum volume of 16.8 liters of water per kilogram (2.1 gal/lb) of lobster; Rauch suggests about 8.8 liters per kilogram (1.1 gal/lb); Huguenin (1976) recommends 61.9 liters per kilogram (7.4 gal/lb). McLeese (1956) used an area of 0.4 square meters per 500-gram lobster (4.3 ft^2 per 1.1-lb) which is 120 liters (31.7 gal) assuming a

30-cm (11.8-in) depth. Schuur et al. (1974) suggest an area five by three times the carapace dimensions. Assuming a depth of three times the carapace length, this formula requires 46 liters per kilogram (5.5 gal/lb) for mature lobsters. Schuur et al. (1974) have found that growth rate depends on available area and they present this as a modifying factor in the growth rate equation. The equation's area factor anticipates large areas: 82 square meters (883 ft^2) for 80 percent of maximum growth rate of a 500-gram (1.1-lb) lobster. Obviously, there is need for further study of area effects. For this study, we assume that an area five by three times the carapace dimensions and a depth one to three times the carapace length provide sufficient area and volume for lobsters in individual compartments.

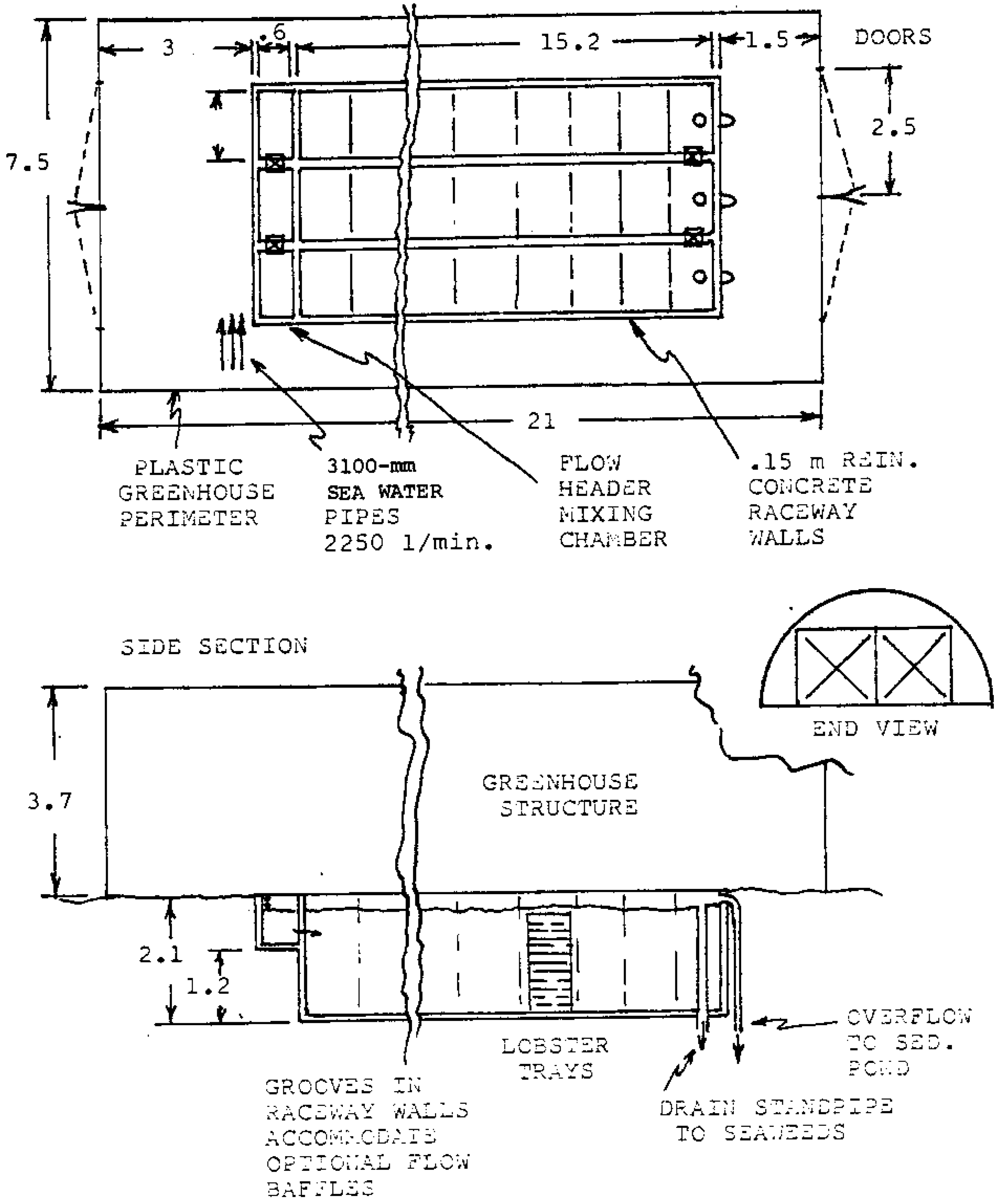
Sheehy (1976) reports lobster biomass densities as high as 74.2 grams per square meter (.015 lb/ft^2) for artificial triple-chamber habitats placed in natural flat bottom areas. Extensive farming then requires 7 square meters ($75ft^2$)per adult lobster where feed and physical separation are not possible. A bottom culture system needs proper habitat spacing to substantially decrease area requirements. A generous feeding schedule should be maintained.

Water Circulation and Replacement Flow Rates

Huguenin (1976) suggests the use of .83 liter per minute per kilogram (.1 gal/min/lb) of biomass in an open system where no water is recycled. Gates et al. (1974) suggest .25 liter per minute per kilogram at 21°C (.03 gal/min/lb at 70°F) and .17 liter per minute per kilogram at 10°C (.02 gal/min/lb at 50°F). Stewart et al. (1972) use two changes of water volume per hour (approximately .35 l/min/kg (.042 gal/min/lb)) if there is a volume of 10.4 liters per kilogram (1.25 gal/lb). Hughes et al. (1972) use a closed system with aeration, filtration, and recirculation with replacement of water every two weeks.

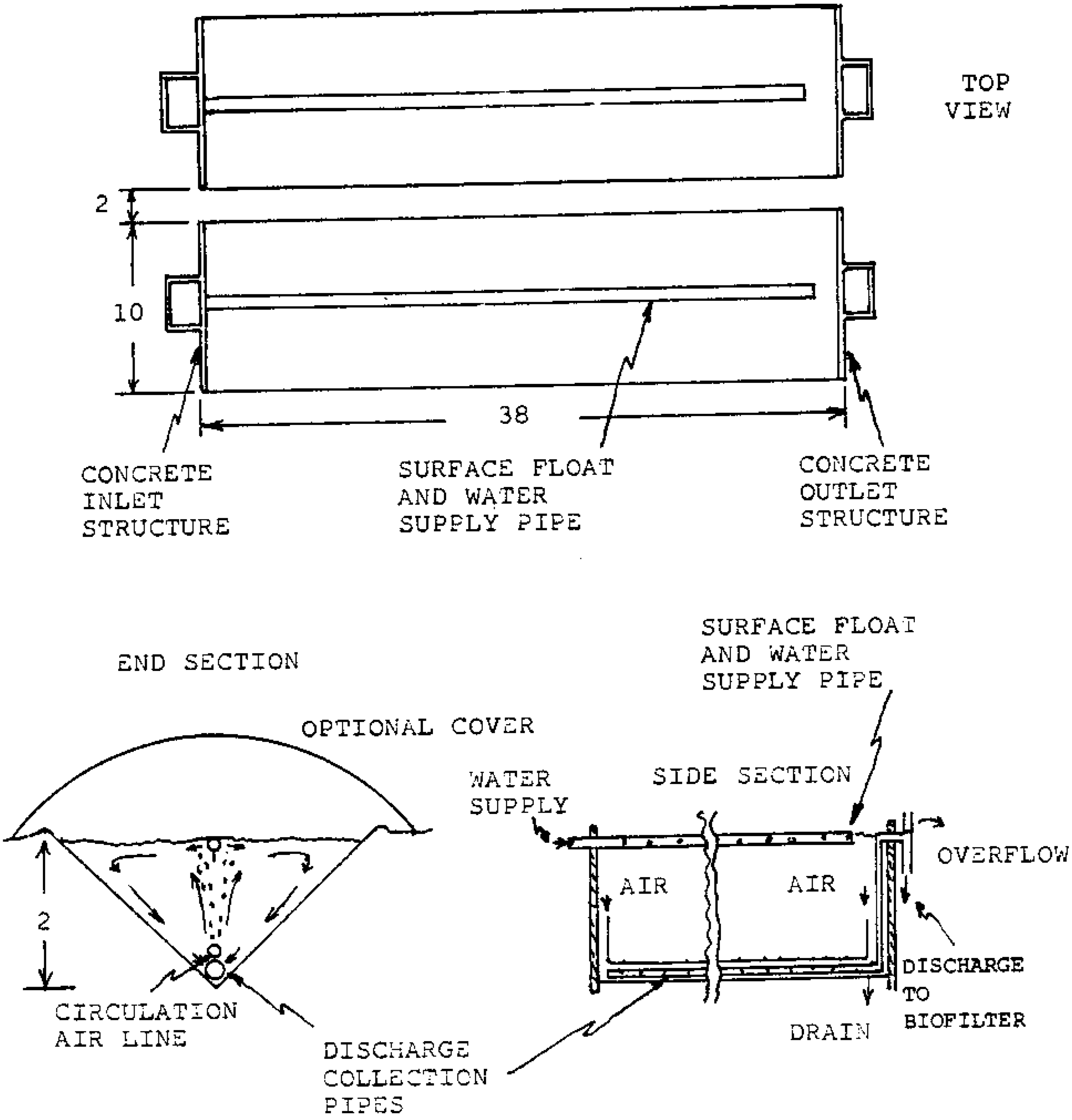
Water flow maintains oxygen levels and removes wastes. The volume of water, the water temperature, the cleanliness of the system, and the efficiency and rate of water treatment and recirculation determine the water replacement rate. We selected a conservative flow value of .83 liter per minute per kilogram (.1 gal/min/lb). This figure combines the volume of fresh water and high-quality recycled water.

FIGURE 14 PILOT PLANT LOBSTER RACEWAYS
(one of two sets)



NOTE: Dimensions in meters

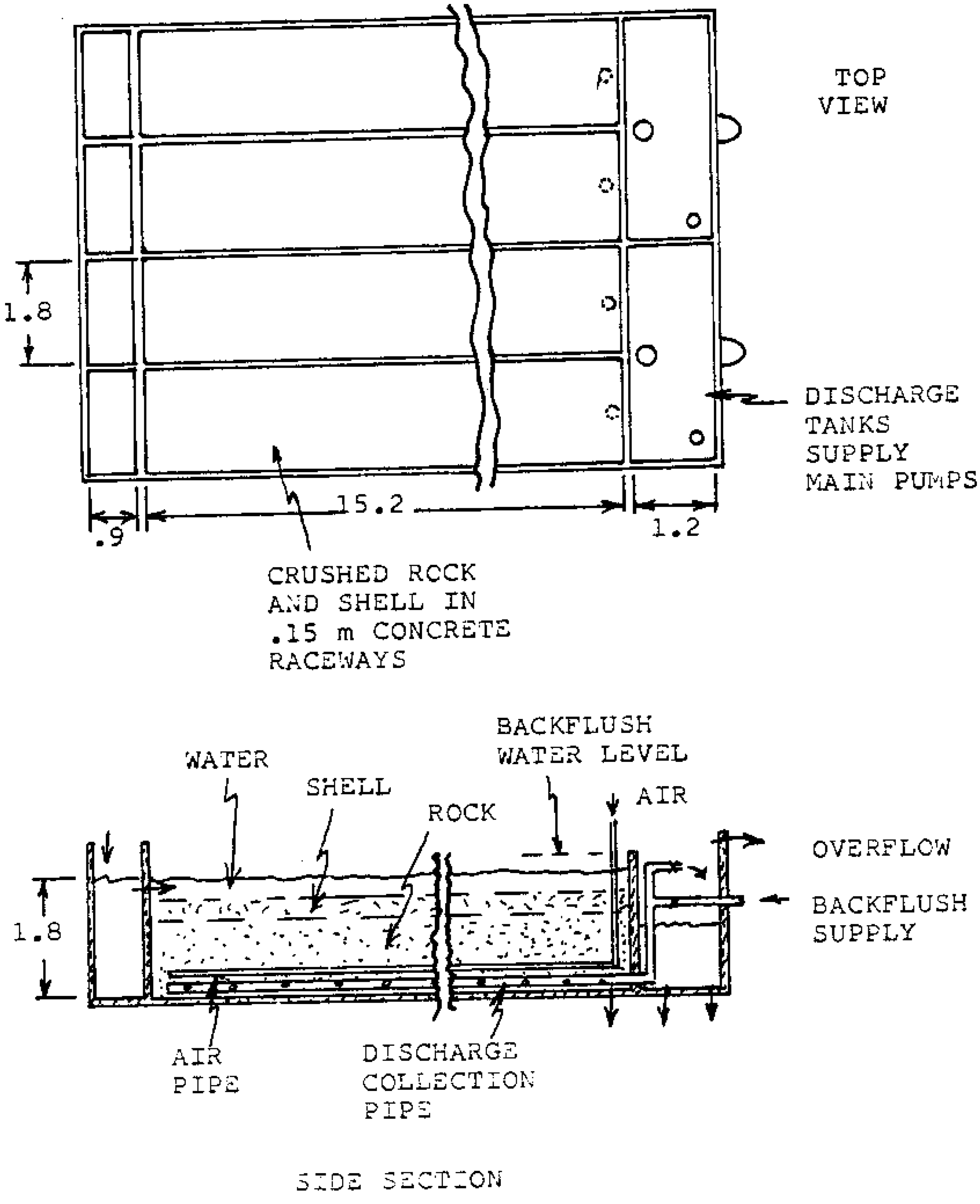
FIGURE 15 PILOT PLANT SEAWEED PONDS
(one of two sets)



NOTE: Dimensions in meters

Source: Huguenin 1976

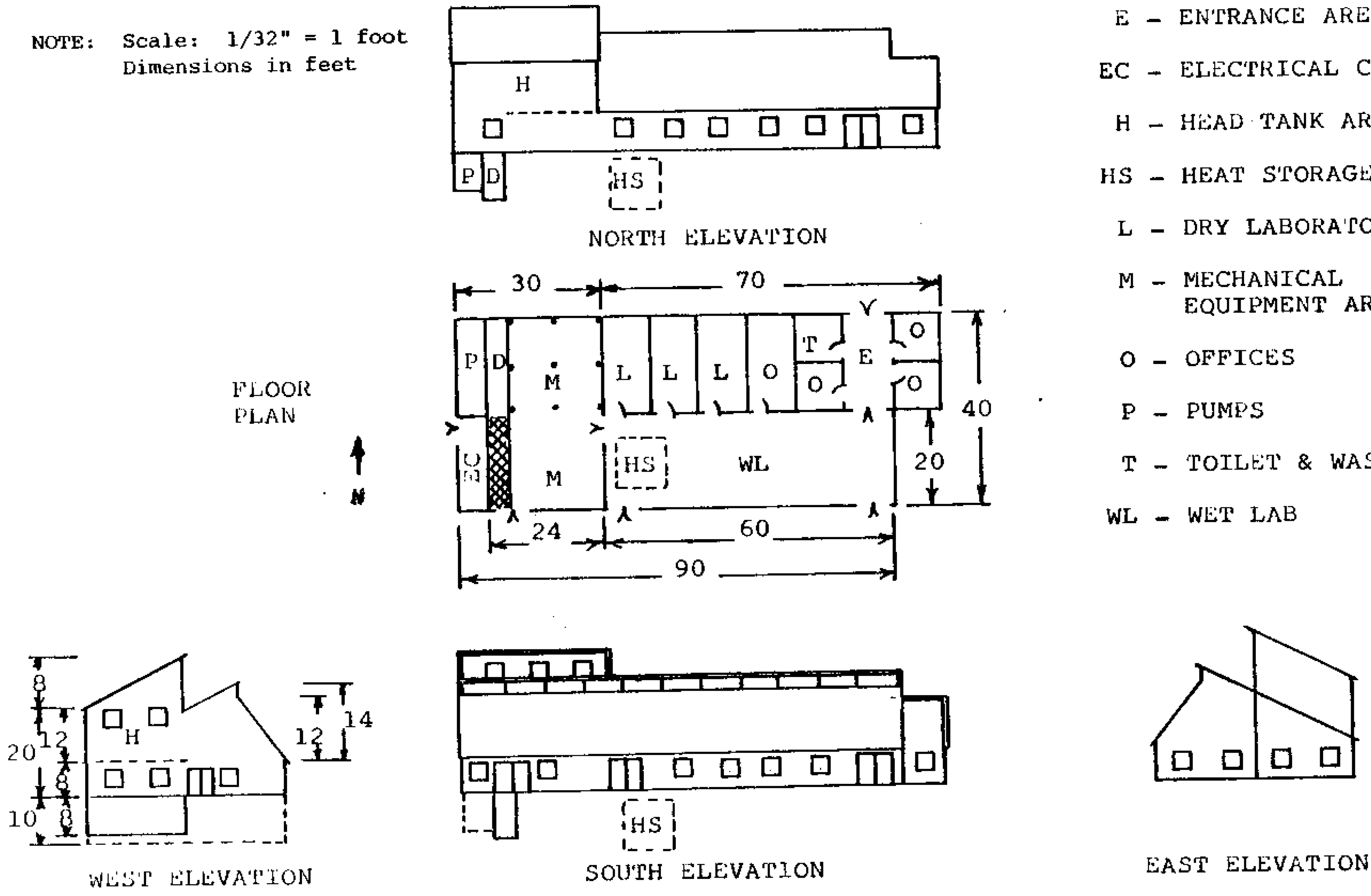
FIGURE 16 PILOT PLANT BIOLOGICAL FILTERS



NOTE: Dimensions in meters

FIGURE 17 MARICULTURE BUILDING

NOTE: Scale: 1/32" = 1 foot
Dimensions in feet



NORTH ELEVATION

FLOOR PLAN

WEST ELEVATION

SOUTH ELEVATION

EAST ELEVATION

D – DRAIN CHANNEL
E – ENTRANCE AREA
EC – ELECTRICAL CONTROL
H – HEAD TANK AREA
HS – HEAT STORAGE TANK
L – DRY LABORATORIES
M – MECHANICAL EQUIPMENT AREA
O – OFFICES
P – PUMPS
T – TOILET & WASHROOM
WL – WET LAB

FIGURE 18 HEAT REQUIREMENTS FOR OPEN-SYSTEM CULTURE (5000 lobsters/year; 4500 liters/minute flow)

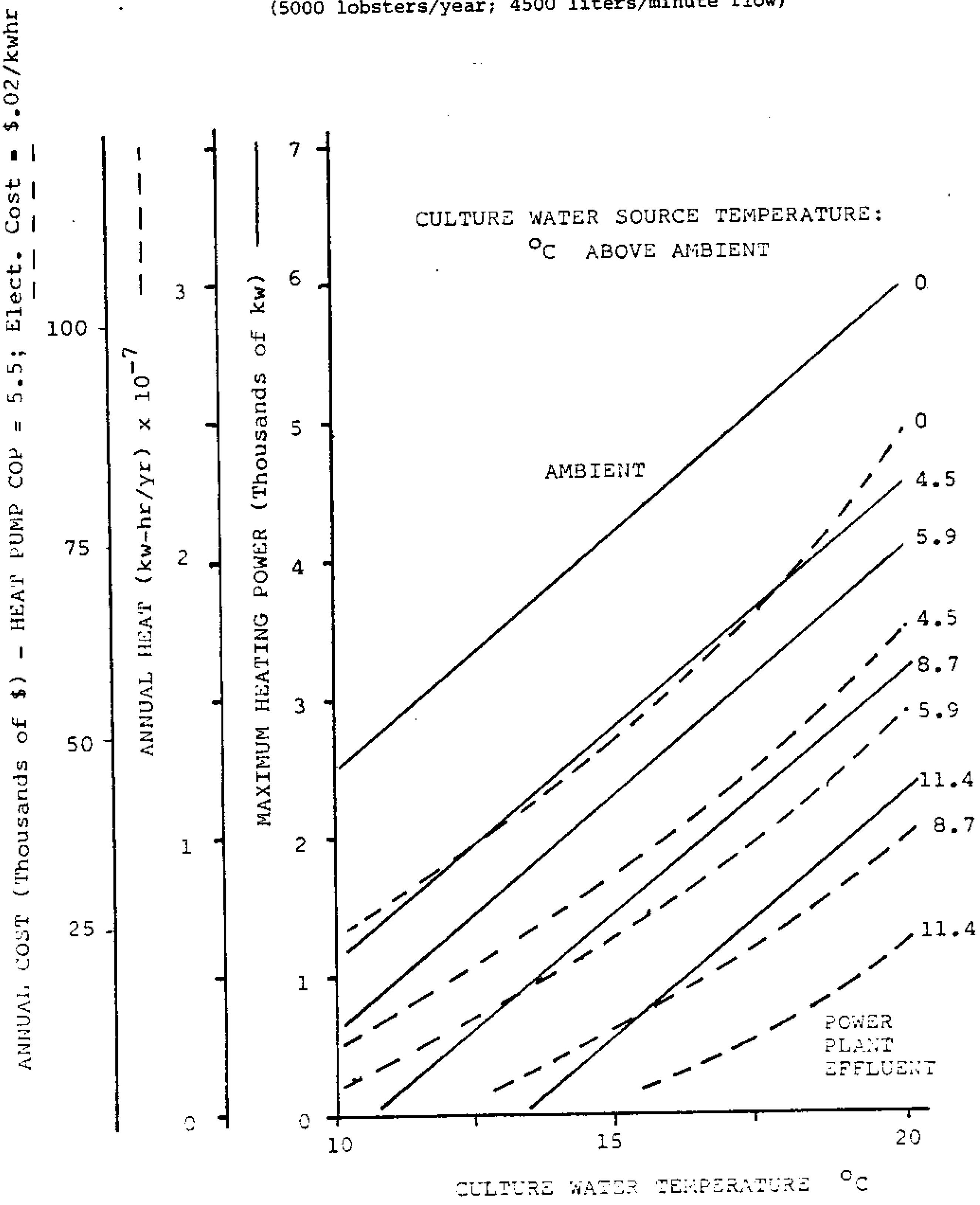
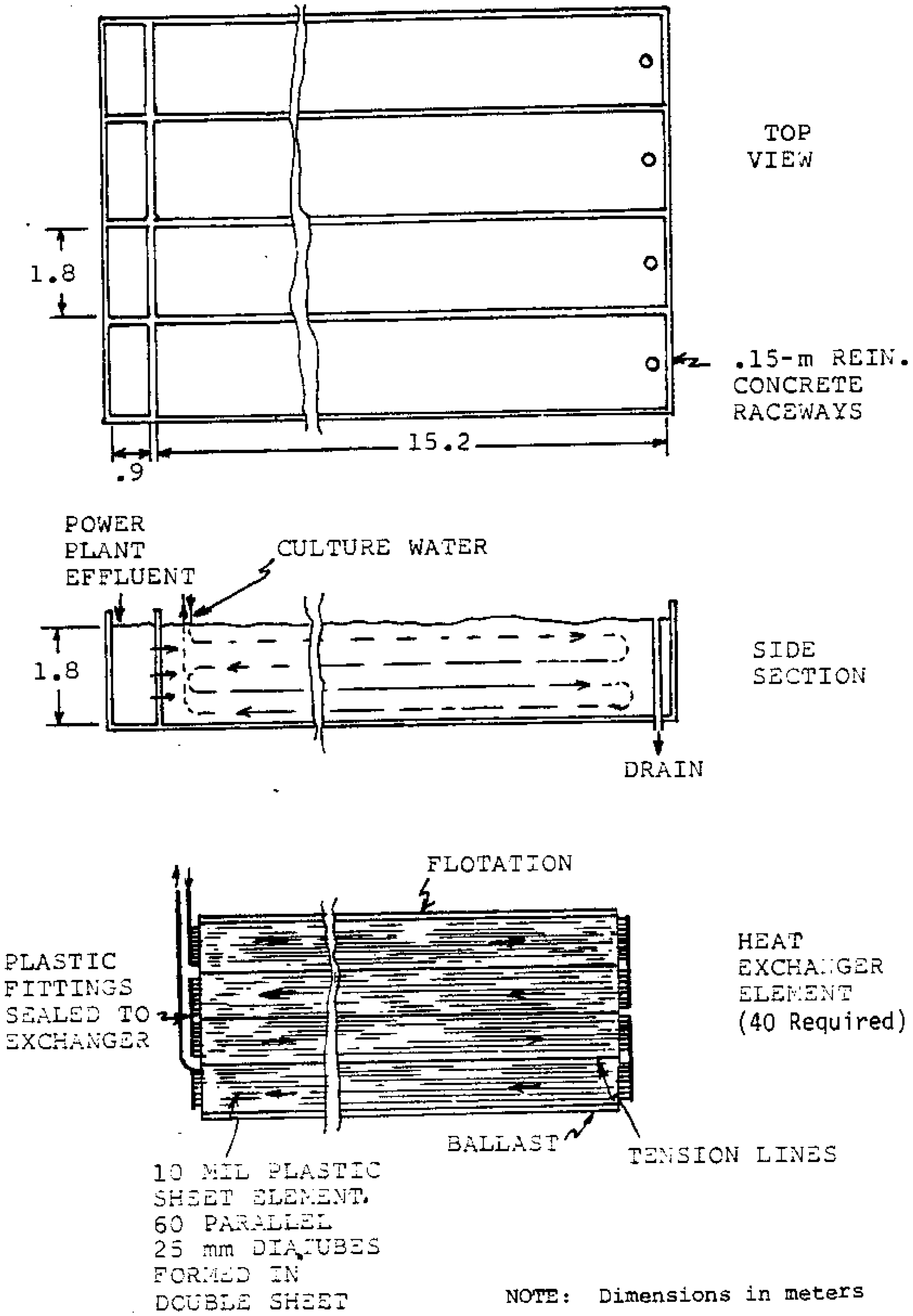


FIGURE 19 HEAT EXCHANGER



NOTE: Dimensions in meters

FIGURE 20 GREENHOUSE COVER COMPARISONS: NIGHT HEAT TRANSFER

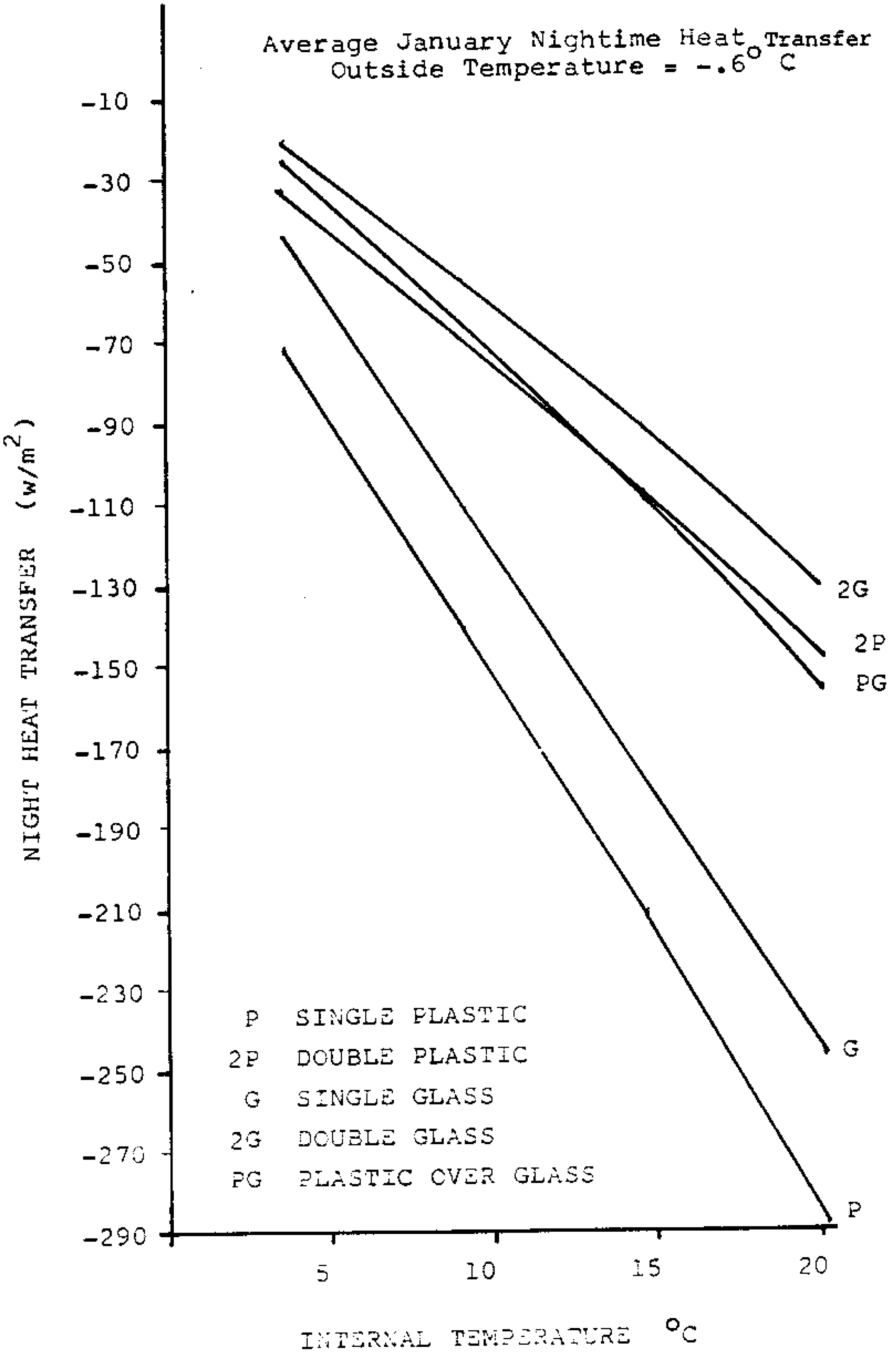


FIGURE 21 GREENHOUSE COVER COMPARISONS: MAXIMUM MIDDAY SOLAR HEAT

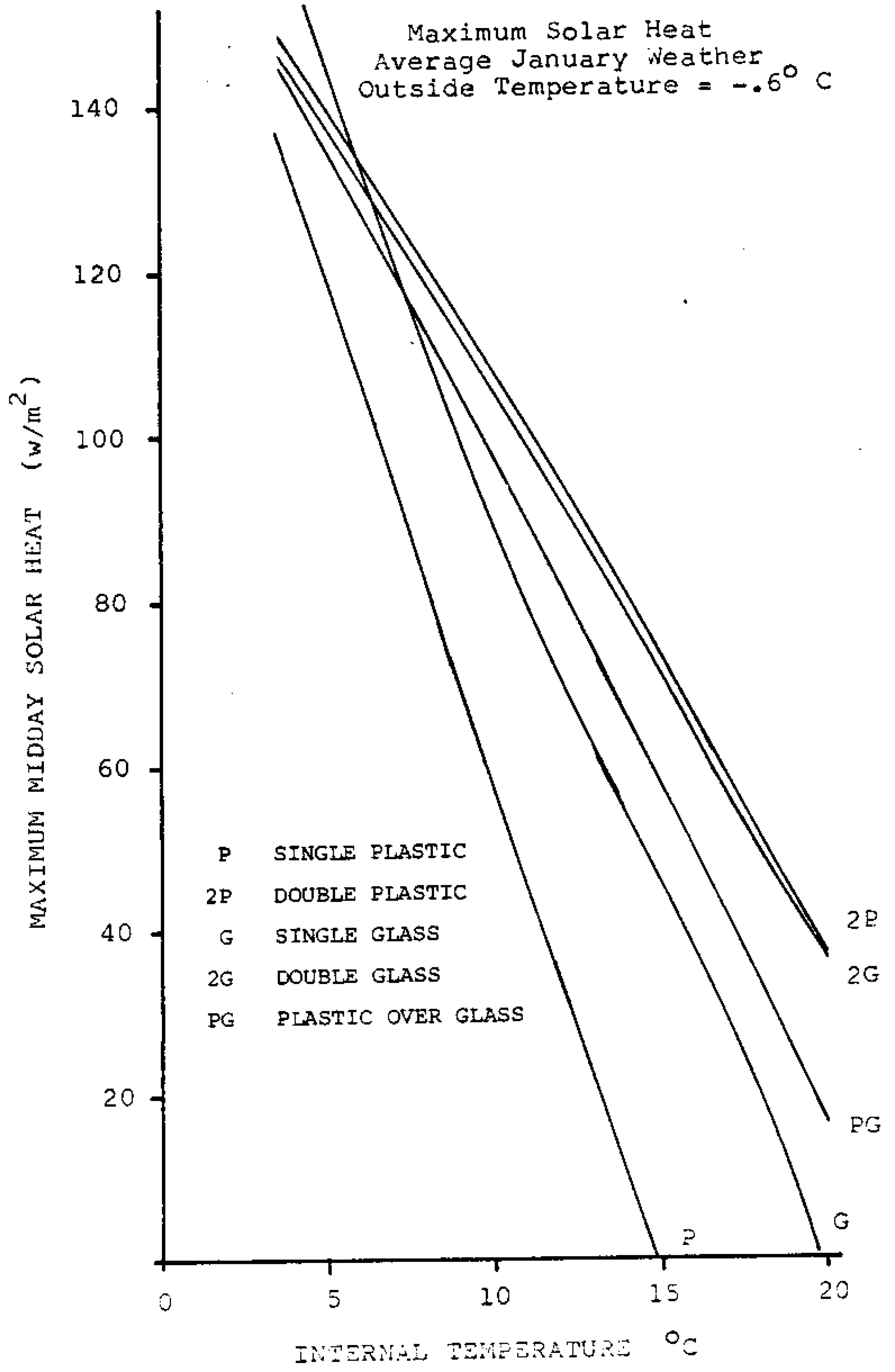


FIGURE 22 GREENHOUSE COVER COMPARISONS: AVERAGE DAILY HEAT TRANSFER

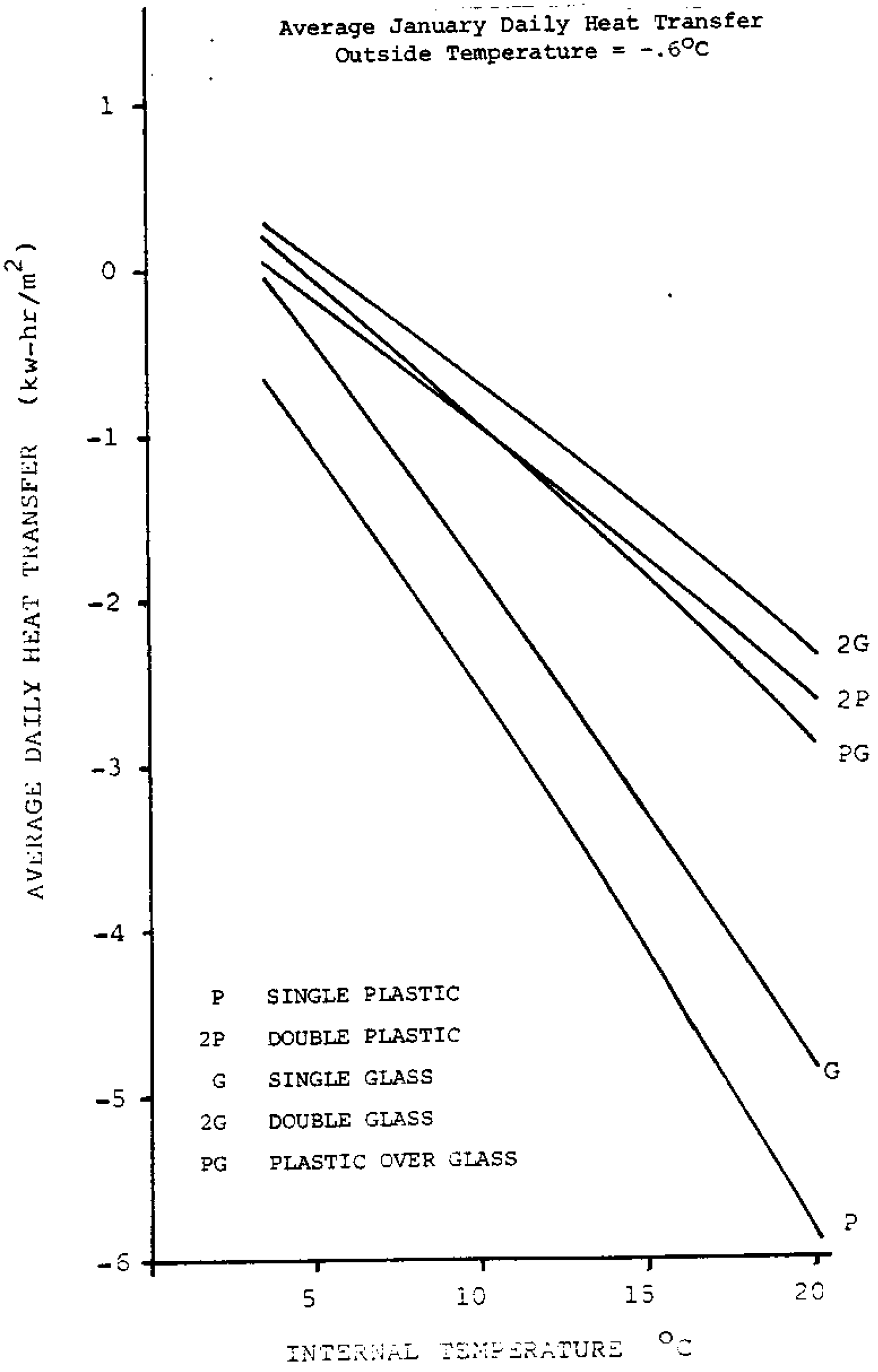


FIGURE 23 PILOT-PLANT HEATING SYSTEM

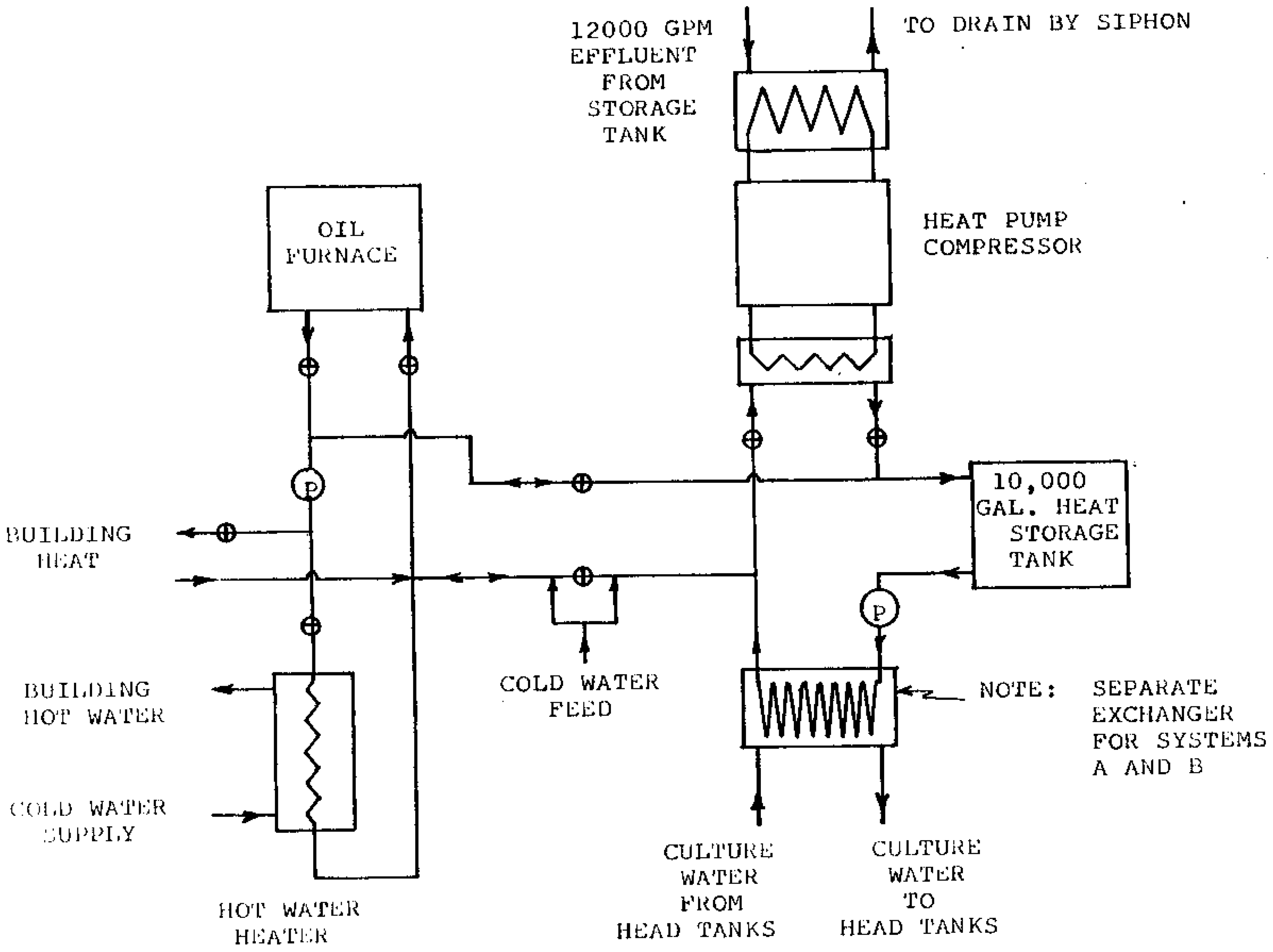
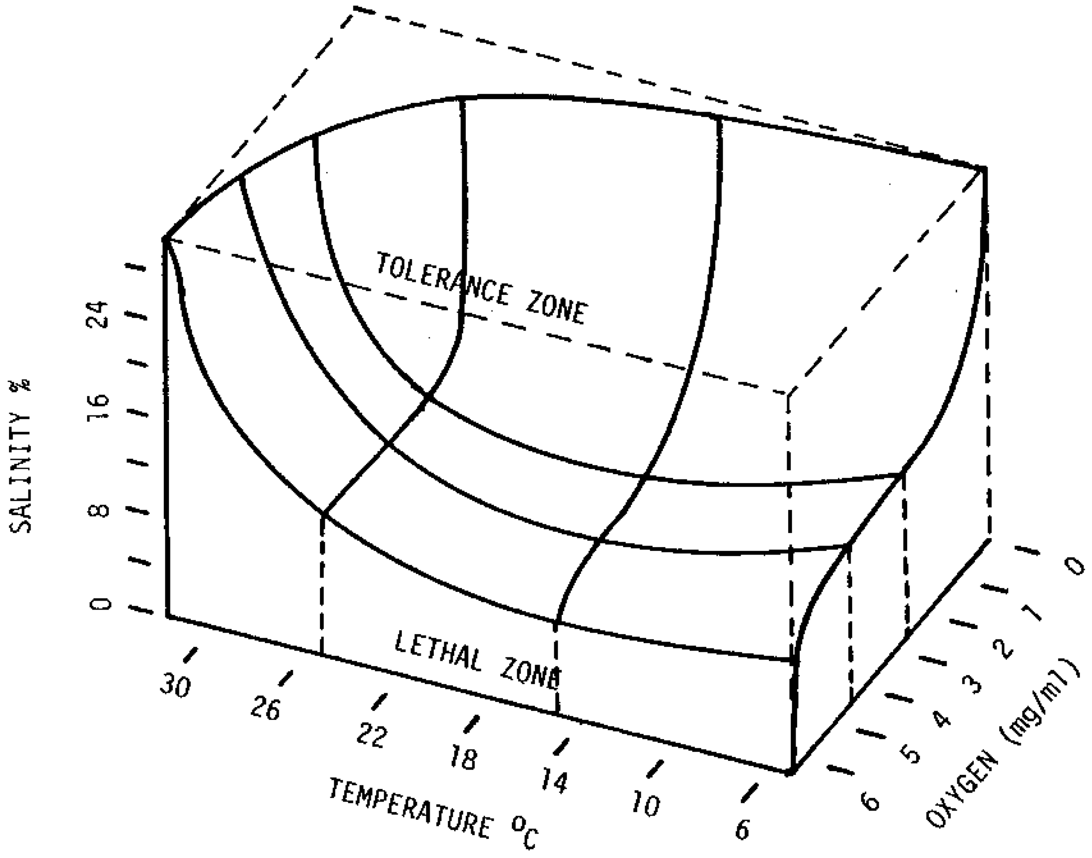
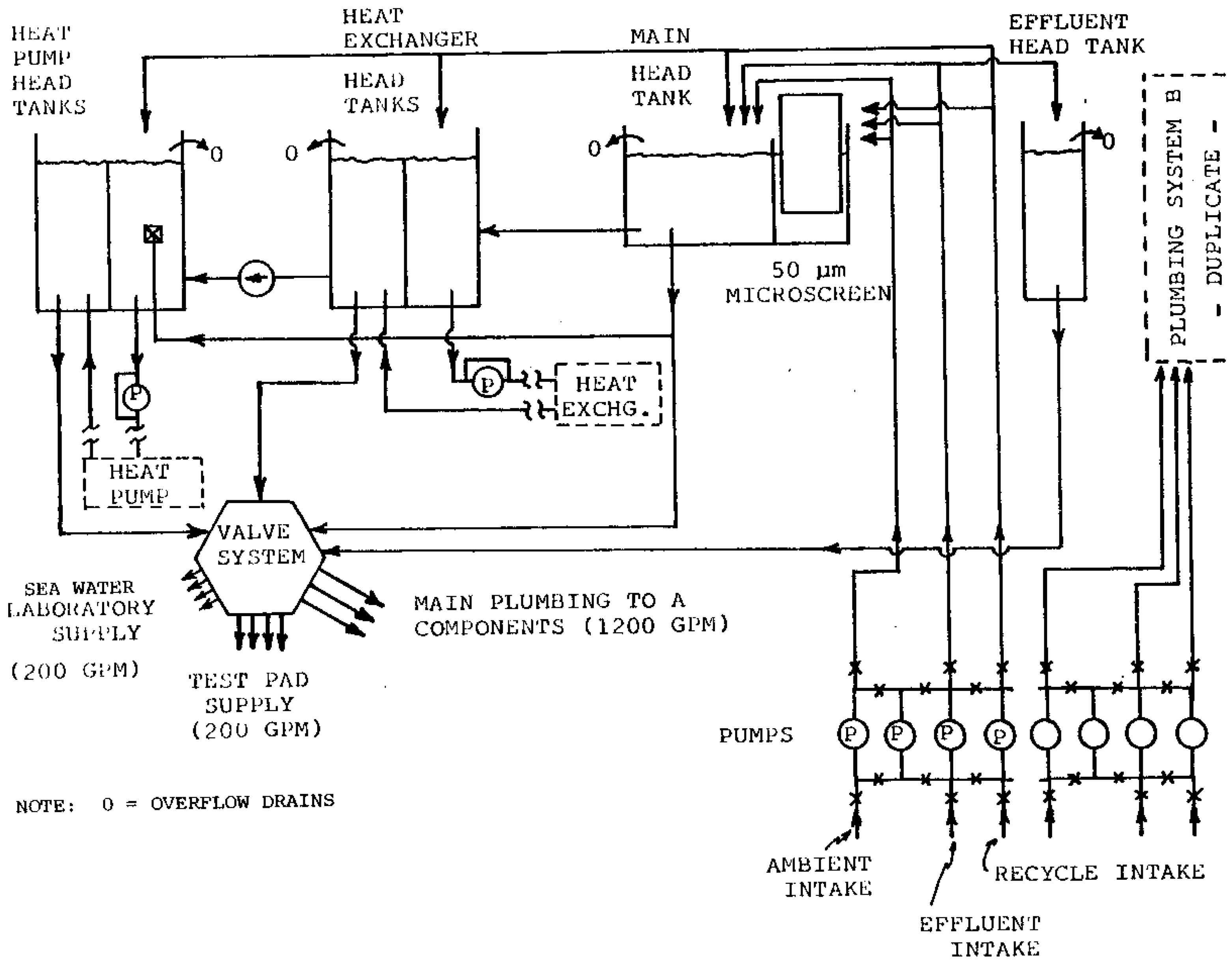


FIGURE 24 LOBSTER TOLERANCE TO TEMPERATURE, SALINITY, AND DISSOLVED OXYGEN



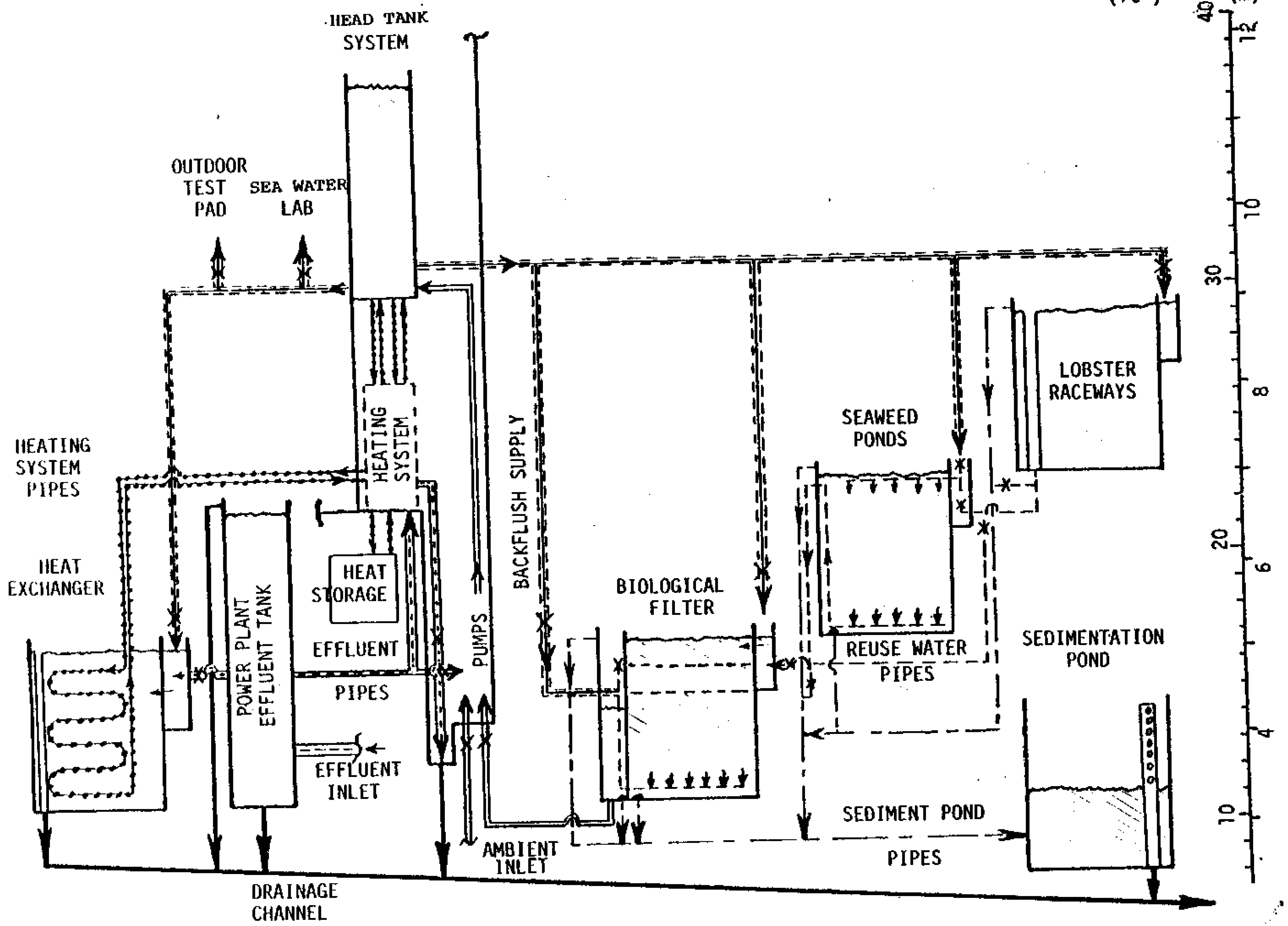
Source: McLeese 1956

FIGURE 25 PILOT-PLANT SEA WATER SUPPLY SYSTEM



NOTE: 0 = OVERFLOW DRAINS

FIGURE 26 COMPONENT ELEVATIONS AND MAIN DISTRIBUTION PLUMBING SCHEMATIC



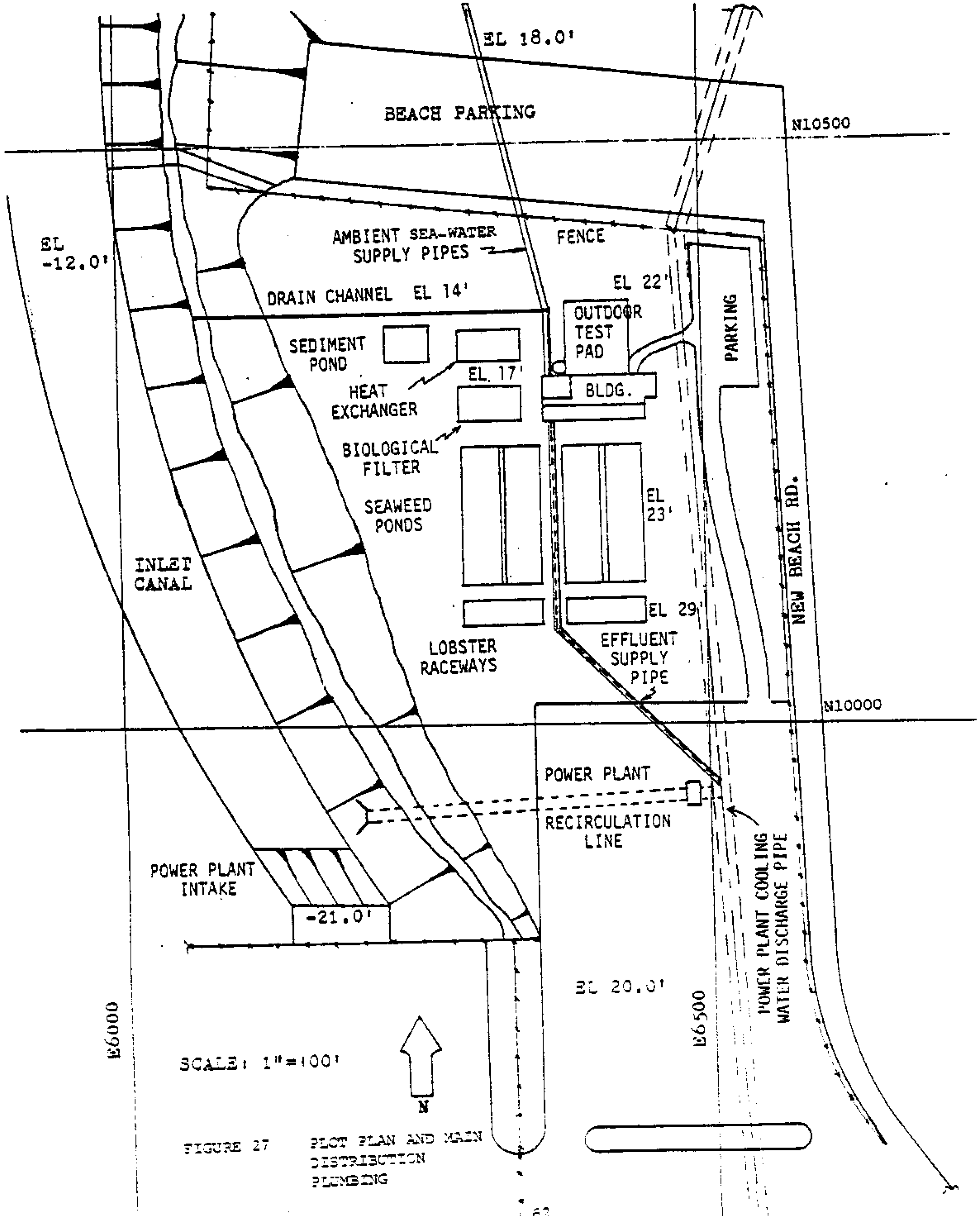


FIGURE 27 PLOT PLAN AND MAIN DISTRIBUTION PLUMBING

FIGURE 28 PLOT PLAN AND MAIN DISTRIBUTION PLUMBING

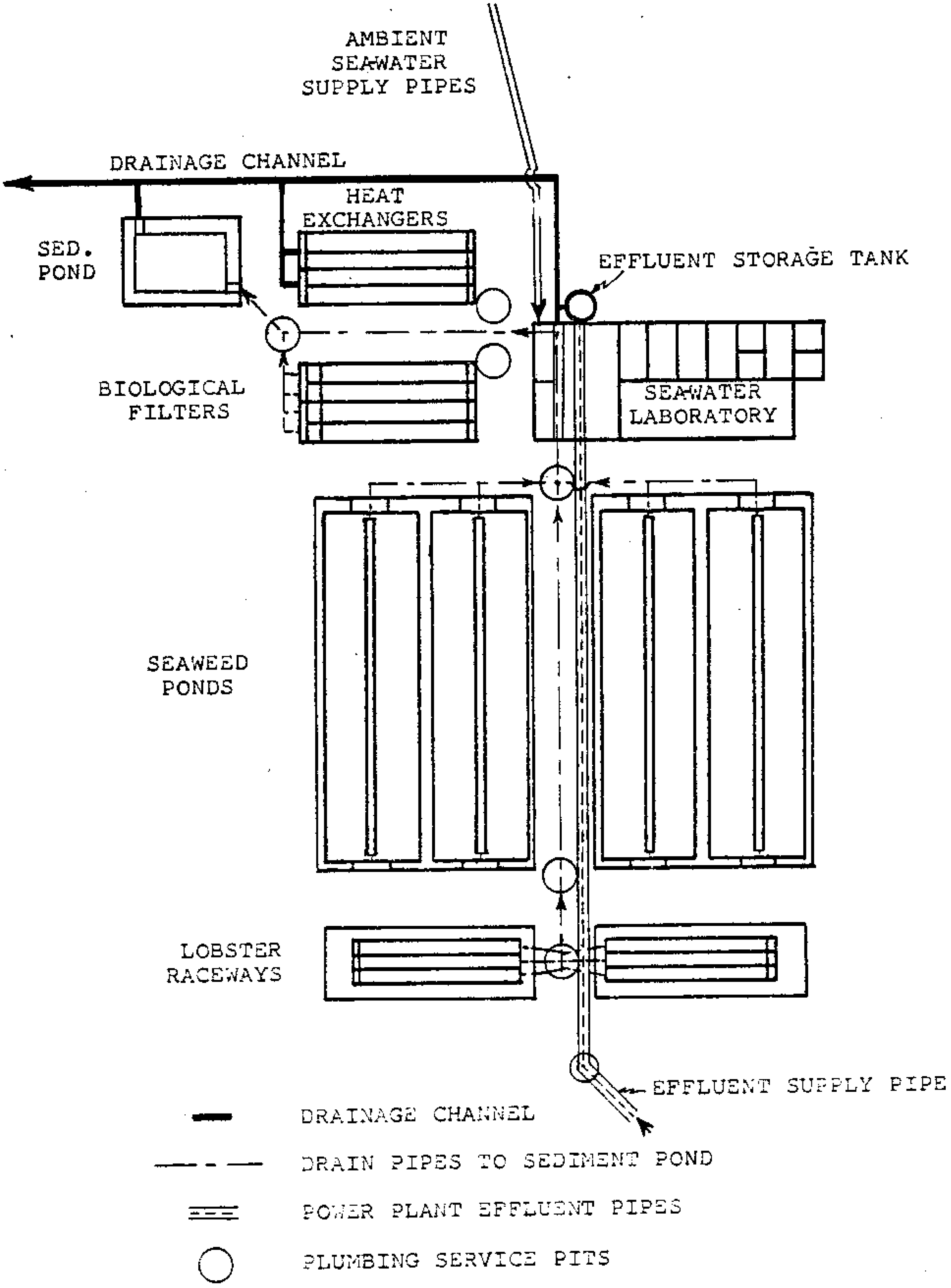


FIGURE 29 PLOT PLAN AND MAIN DISTRIBUTION PLUMBING

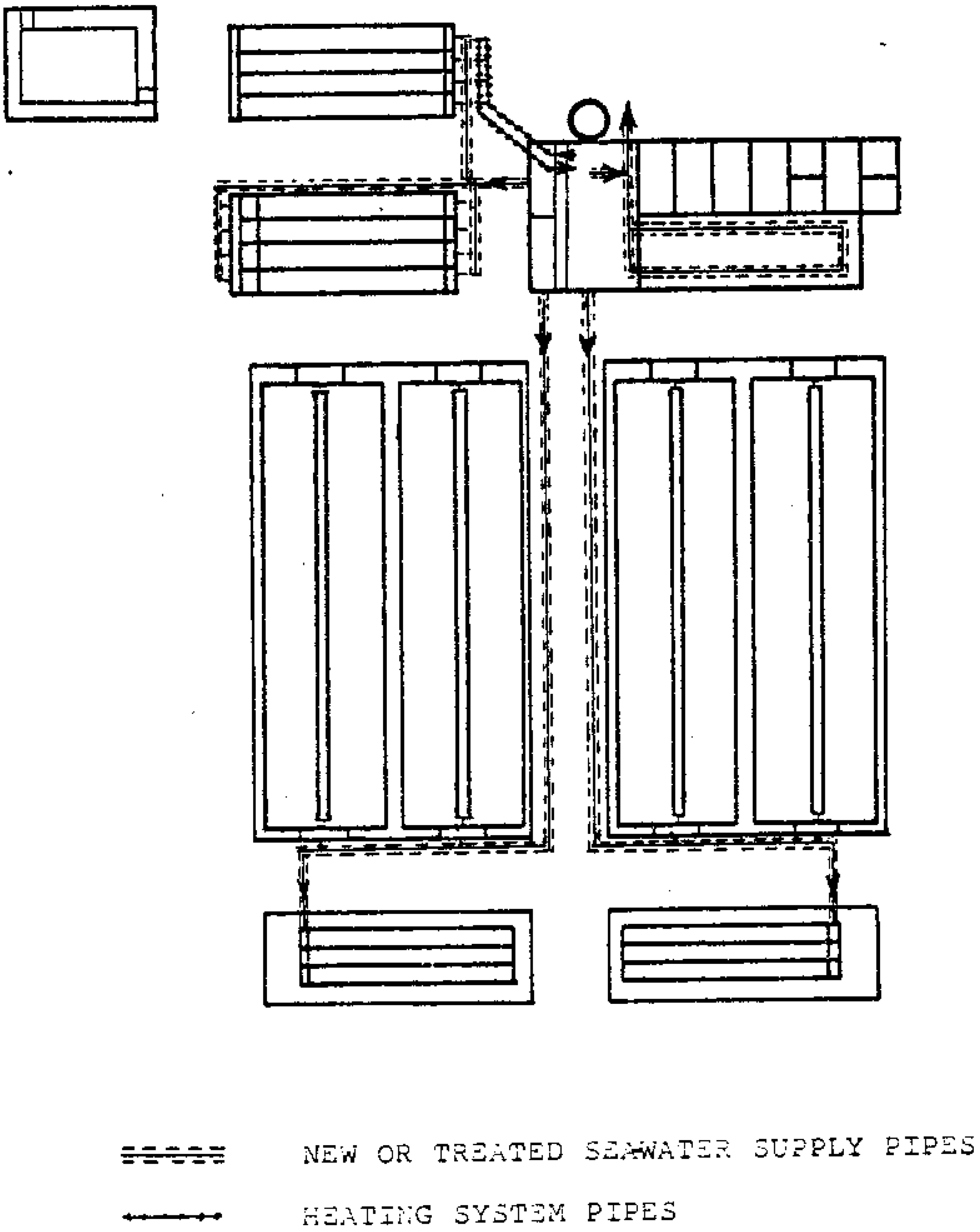
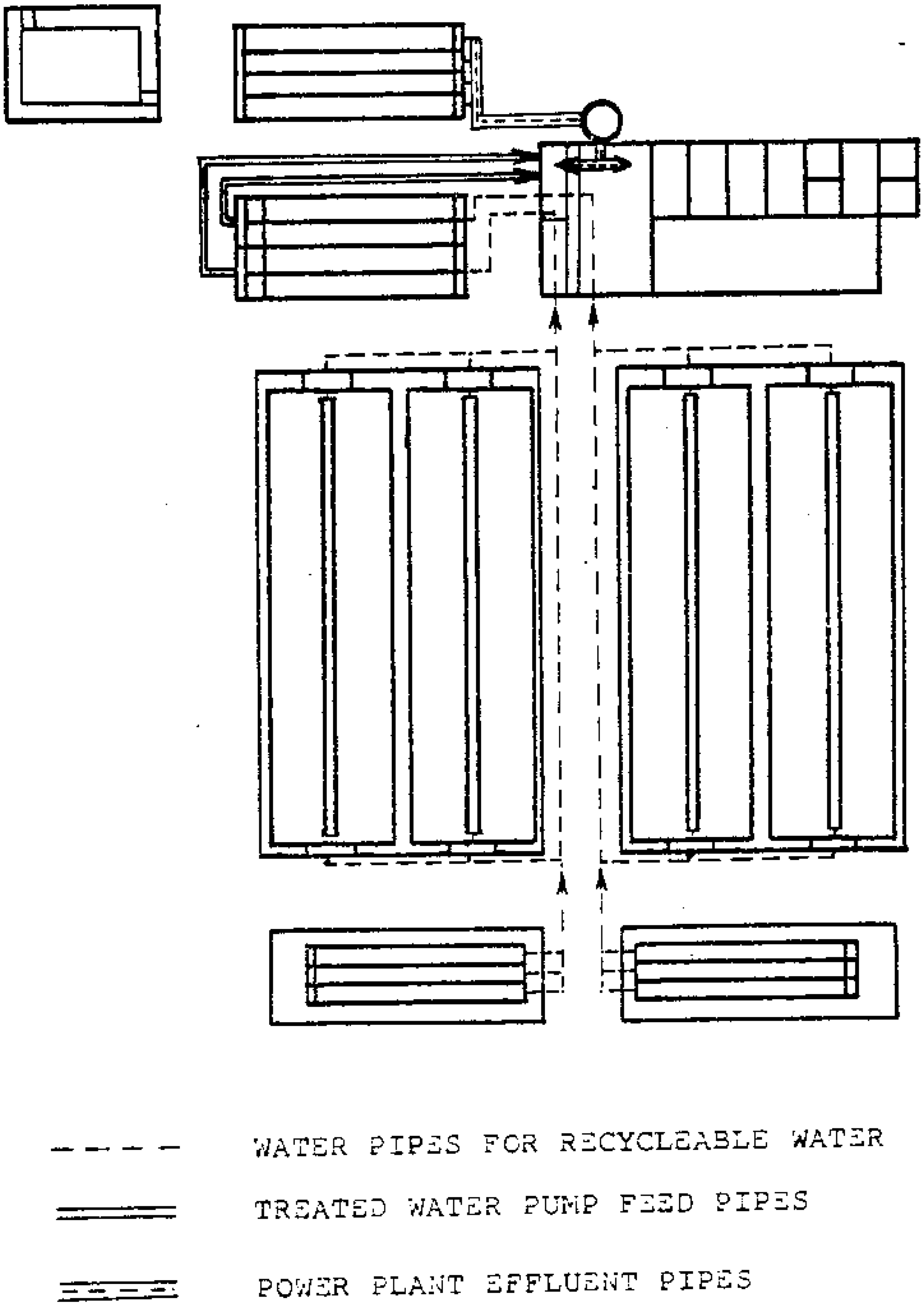


FIGURE 30 PLOT PLAN AND MAIN DISTRIBUTION PLUMBING



FACILITY DESIGN

Lobster Culture

The overall lobster culture scheme designed for the pilot-plant facility incorporates the system presented in Figure 10 for large lobsters and can accommodate the systems shown in Figures 12 and 13 for juveniles. Since space required for juvenile cultures is relatively small, pilot experimentation for this stage will be housed in a large, open, indoor, sea-water laboratory and in a flexible outdoor test pad.

Figure 14 presents the design for adult culture tanks. There are notable differences between the pilot-plant tanks and commercial-scale systems. The raceways in the former are covered to reduce heat loss and maintain a suitable atmosphere for winter experiments. The pilot-plant culture is not subtidal and can be completely drained for cleaning. This allows flexible operation at the pilot-plant stage of mariculture development. The system provides a controlled gravity flow to and from the culture raceways.

Culture-water options are ambient sea water, heated sea water, and power-plant effluent. These can be used independently or in combination and can be prefiltered and treated for recycling. A total raceway flow of 4500 liters per minute (1200 gal/min) with a volume of 160,000 liters (42,300 gal), based on the parameters in Table 5, will maintain a 5000-lobsters-per-year pilot plant.

Seaweed Culture

The lobster pilot plant will produce an estimated 680 grams of unionized ammonia daily (Schuur et al. 1974). Other forms of nitrogen (N) introduced by the culture will average 15 kilograms (22 lbs) per day (assuming a feed to lobster conversion of 8 to 1). Total N Levels (including NH_4^+, NO_3, NO_2, and particulate N) in the lobster culture effluent will average at least 2.3 milligrams per liter (1.92×10^{-5} lb/gal)--an appropriate concentration for highly efficient removal by seaweed cultures. The seaweed culture-nutrient removal system in Figure 15 was designed using reasonably optimistic values presented by Huguenin (1976).

Assuming that 40 percent of the nitrogen in the lobster culture effluent is in usable form and that other nutrient levels balance appropriately, seaweed growth will absorb 6 kilograms (13.2 lb) of nitrogen per day. With about 4 percent of dry seaweed biomass as nitrogen, a total of 150 kilograms (331 lb) dry weight of seaweeds are produced each day. Dry seaweed sells at $1.10 per kilogram ($1000/ton), so the 41,000 kilograms (45 tons) of seaweeds raised per year could generate $45,000. Assuming a 15 percent biomass increase per day and a dry-weight to wet-weight ratio of .1, the facility must maintain a consistent crop of 10,000 kilograms (22,000 lb) wet weight to achieve production goals. This means the average density is 6.7 kilograms per square meter (1.37 lb/ft^2) over 1500 square meters (22,000 ft^2) of culture area. Given this production goal, we have designed four 10- by 38-meter (33- x 125-ft) culture ponds costing approximately $20,000, with operating costs under $10,000 per year (Huguenin 1976).

The seaweed cultures proposed for this pilot plant use plastic pond liners instead of the sealed asphalt construction suggested by Huguenin. This permits cheaper conversion to a flat-bottom pond if pilot experiments in mass bottom culture were desired.

The economics of large-scale seaweed culture appear to be much more favorable than intensive lobster culture at this time. This,plus the nutrient-stripping capability of seaweeds,provides sufficiently positive incentive for including seaweed cultures in the pilot-plant design.

Biological Filter

Several factors indicate the need for a biological filter in a sea-water recycling system at the pilot facility.

1. Power-plant contaminants may seriously limit direct use of heated effluent for food culture.
2. Midwinter power-plant shut downs could endanger large-scale experiments by causing water temperature changes.
3. Optimum culture temperature requires heating water above power-plant effluent temperature in midwinter.
4. Seaweed culture presents many unknowns and cannot be relied upon as the only treatment for recycled water.

5. Because of the large surface area required, seaweed culture inherently imposes a large heat loss during the winter.

Although biological filters are the most common means of conditioning aquarium water for reuse, there are gaps in design information concerning their applicability in large culture systems. Burrows and Combs (1968) present a design based on small-scale experiments that they feel is applicable to large-scale culture. The filter consists of a 1.3-meter (4.3-ft) layer of sharp rock 1.3 to 16 millimeters (.05 to .63 in) in diameter covered by a .3-meter (11.8-in) layer of crushed oyster shell 6 to 19 millimeters (.24 to .75 in) in diameter.

Both rock and shell provide surfaces for culture development of nitrifying bacteria. In addition, the shell supplies calcium carbonate, the base for producing calcium nitrate. Without this base, nitrous and nitric acids would form, lowering pH and threatening aquatic cultures. Proper pH maintenance minimizes the solubility of toxic heavy metals. The shell also maintains trace minerals in the culture water. The shell physically filters particulates which are then removed by backflushing and air agitation without disturbing the bulk of the bacterial community in the rock layer. Filamentous bacteria and algae may form a mat over the shell surface which hinders particulate scrubbing. Biweekly chemical treatment during backflushing eliminates this problem.

Burrows and Combs (1968) suggest designing the biological filters with 40 liters per minute per square meter (.90 gal/min/ft^2) of filter surface area. The design in Figure 16 for the 5000-lobster plant uses this value. Filter design values suggested by Spotte (1970) call for areas two to three times greater than that used in the selected design. We rationalize using Burrows and Combs' figures because we expect seaweed culture to reduce the load on the biological filter.

AN ALTERNATIVE

Dwivedy (1973, 1975) reports a promising alternate subsystem for recirculation--the foam fractionation device. This device removes dissolved and suspended organic material from the water and prevents ammonia buildup. This technique does not remove ammonia. However, Dwivedy (1975) suggests that chlorination after foam fractionation could remove ammonia in 15 to 20 minutes. Activated carbon removes any excess chlorine in the water. Unfortunately the process also removes oxygen molecules so aeration may be necessary.

The foam fractionation device alone could be used before the biological filter to remove most of the organics and oxygenate the water. The device could sharply reduce the size requirement of the biological filter and eliminate filter overload during peak organic loads. Such a system greatly reduces the build-up of nitrates in closed systems. The foam produced is rich in organics and might be used in algae culture.

Since the foam fractionation device is not yet well established, we have not included it in this facility design. Its promising aspects certainly warrant future consideration.

Building Facility

The pilot-plant building (Figure 17) provides ample space for three faculty investigators plus related research assistants and support personnel. Office space was calculated on the basis of 9.3 square meters (100 ft^2) per investigator. An additional 18.6-square meter (200-ft^2) office is included for research assistants. Three dry laboratories at 18.6 square meters (200 ft^2) each provide facilities for chemical analysis. An open sea-water laboratory of 111 square meters (1200 ft^2) can support small-scale mariculture research projects or larval and juvenile cultures for a large-scale lobster-culture pilot project. A 15.2- by 22.9-meter (50-x 75-ft) outdoor test pad provides additional space for intermediate-scale sea-water cultures (Huguenin 1976).

The building includes a 12.2-by 9.1-meter (40-x 30-ft) space for mechanical systems--water pumps, air compressors, heating systems, an electrical control panel, and storage. Locating pumps at 4.3-meters (14-ft) elevation minimizes the suction head and places them well above maximum high tide at 3.3 meters (11 ft). A drain channel next to the pumps holds pipes and valves for water distribution. Head tanks, situated on a second floor at 9.1 meters (30 ft), provide a maximum head at 11.6-meters (38-ft) elevation for water flow control throughout the facility.

Angled at 50 degrees, the roof on the southern exposure of the building provides an optimum surface for future installation of flat-plate solar collectors capable of supplying most of the heat requirements for the building. Solar heating is not included in the present design, as heating the building is only a small fraction of the heating requirements for outdoor cultures. The entire facility will draw heat from the main heat pump. An auxiliary oil-heat system will heat the building when the power plant shuts down. Oil heat provides a necessary backup for any future solar heating system as well.

Heating System

Maintaining optimum culture temperature for large-scale operations can represent an enormous expense. It requires careful consideration of heating systems and culture water use, but is essential to successful lobster production.

For example, optimum water temperature range for lobster growth is 15 to 23°C (59-73.4°F). Lower temperatures slow growth rates, but are not detrimental to health except immediately after the lobsters moult. During the post-moult period, sudden temperature changes should be avoided. Lobsters adapt to temperatures up to 32°C (89.6°F), but mortality rates due to disease or short-term failures in the plumbing system will increase at elevated temperatures. Figure 7 (McLeese and Wilder 1958) summarizes the effects of rapid temperature changes.

Direct heating of water by a fossil fuel system in an open-flow (once-through) culture would not be practical (Figure 18). Economics restrict open-system culture to the warm water from power-plant effluent available either through direct use or by means of a heat exchanger. While direct use of effluent would be less costly, its use currently is prohibited by trace radioactive contaminants and condenser cleaning chemicals (Tables 1 and 2). Indirect use of effluent heat using a heat exchanger is a necessary component of open-system culture, therefore.

EXCHANGER DESIGN

The proposed plastic-film heat-exchanger elements (Figure 19) have not been tested, but they promise a low-cost option for heating culture water for the 5000-lobster project. These elements can heat the entire culture water flow of 4500 liters per minute (1,200 gal/min) to at least 9°C (16.2°F) above ambient. Standard pipes and fittings may be substituted in the heat exchanger channels if initial tests indicate the plastic sheet elements are not feasible.

The heat exchanger channels receive up to 45,000 liters per minute (12,000 gal/min) of effluent, useful for the study of equipment or culture systems deployed directly in power-plant discharge channels. The channels also provide additional culture space when not used for heat exchangers.

RECYCLING THE WATER

A water recycling system in the facility requires a replacement flow of 5 percent of open-system needs. Maintaining optimum culture temperature is potentially economically viable. Heating-load calculations must include heat loss within the system as well as heating replacement water.

Since open water surfaces cool rapidly, we have investigated alternative cover materials for outdoor culture. Figures 20, 21, and 22 illustrate results of theoretical heat-loss calculations for several types of covers. Double-plastic covering performs well compared with high-cost, double-glass greenhouse structures. On the basis of a favorable heat balance and low capital cost, we further investigated the use of double-plastic greenhouses to cover the outdoor components of a recycling system.

Table 7 presents information on heating requirements for a recycling water system. Results include a variety of system component coverings. Zahradnick et al. (1976) calculated temperature and heat loss for uncovered components on the basis of average January weather conditions. We calculated total annual heat losses using average monthly weather conditions. Temperature and heat-loss for covered (double-plastic greenhouses) components were calculated from graphs presented by Walker and Duncan (1973) using a design temperature of -15°C (5°F). In all cases in Table 7, we assumed that the entire 4500 liters per minute, (1200 gal/min) water flow ran in series through the lobster and seaweed cultures and biological filters except where arrows indicate a seaweed-culture bypass.

Calculations of electrical input and costs assume that a heat pump can extract heat from the power-plant effluent and transfer it to culture water with an estimated 5.5 annual average coefficient of performance (COP equals

TABLE 7 *Pilot plant heat requirements*

System covering scheme

Lobster raceways Seaweed ponds Biological filters	U[1] U U			C[2] U U			C C U			C C C			C ↓ U			C ↓ C		
Heat losses:	°C[3]	kw[4]	gw-hr[5]	°C	kw	gw-hr	°C	kw	gw-hr	°C	kw	gw-hr	°C	kw	gw-hr	°C	kw	gw-hr
Lobster raceways	20	260	.95	20	87.9	.17	20	87.9	.17	20	87.9	.17	20	87.9	.17	20	87.9	.17
Seaweed ponds	19.21	2600	11.42	19.73	2632	11.56	19.73	386	.848	19.73	386	.848	-	-	-	-	-	-
Biological filters	11.15	126	.442	11.54	126	.442	18.54	130	.471	18.54	49.7	.102	19.73	148	.540	19.73	49.7	.103
Total heat losses	10.76	2986	12.81	11.17	2846	12.17	18.15	604	1.49	18.40	524	1.12	19.28	236	.71	19.58	138	.27
Replacement sea water heating (5% of total flow)	-	181	5.03	-	181	5.03	-	181	5.03	-	181	5.03	-	181	5.03	-	181	5.03
Building heat	-	25	.049	-	25	.049	-	25	.049	-	25	.049	-	25	.049	-	25	.049
Total heat	-	3192	17.89	-	3052	17.25	-	810	6.57	-	730	6.20	-	442	5.79	-	344	5.35
Annual heat cost (COP=5.5; $.02/kw-hr)	$65055			$62727			$23890			$22545			$21055			$19455		
Max. power input (kw)	580			555			147			133			80			63		

[1] U-uncovered component

[2] C-component covered with double plastic structure

[3] Incoming water temperature

[4] Maximum heating power

[5] Annual heat energy

electrical input per unit of heat obtained). We assumed that the exchanger heats the replacement water 9°C (16.2°F) before it enters the heat pump.

OUTDOOR ASPECTS

As is apparent in Table 7, economical operation necessitates covering outdoor cultures. Replacement water requires a large proportion of the heat energy. A highly effective water treatment system could reduce replacement-water needs and substantially decrease heating costs. Even with covered systems, heat costs currently surpass gross income from lobster sales, approximately $10,000 per year. When the lobster culture system includes a seaweed culture system capable of grossing over $55,000 annually, the project seems potentially viable.

HEAT PUMP SYSTEM

The heat-pump system supports a facility operating at full scale year round, including lobster and seaweed production and a biological filter system. A chiller system, rated at 598 kw (170 tons) of cooling and installed as the heat pump, adequately fulfills the heating requirement. The system could be equipped with sea-water heat exchangers and installed for approximately $120,000. The capital cost of a heat-pump system is more than ten times the cost of an equivalent oil furnace and necessitates a long depreciation time (20 years) to justify the equipment.

The heat-pump system, a highly efficient operation, offers low operating costs and low power requirements. Favorable temperature conditions of the power-plant effluent culture-water system help achieve a high coefficient of performance. For at least six months of the year, effluent temperature runs higher than the necessary culture water temperature. To determine the annual average coefficient of performance, we considered seasonal temperature variations and reduced equipment efficiency under low load. A 38,000-liter (10,000-gal) hot-water storage tank in the heating system improves control and reduces periods of low-output operation. Since there are numerous complicating factors in heat-pump performance calculations, the estimates obtained require further refinement. The estimates are reasonable approximations for a complex system.

Power-plant shut downs make the heat-pump system inoperable, a serious drawback in the winter. We have included an auxiliary oil furnace in the design (Figure 23) to cover this contingency. The auxiliary system (160-kw peak) supplies heat to the building and augments heat lost in covered lobster and biological filter systems. It does not supply heat lost in the seaweed cultures or replacement water supply. A sudden temperature drop will not seriously affect seaweed cultures.

Sea-water System

The research nature of the proposed mariculture facility demands simultaneous distribution of ambient and heated fresh sea water as well as powerplant effluent. We have included additional options for filtered or unfiltered sea water and recycled or fresh sea water. Two separate systems, allowing isolated supplies of recycled water, supply the outdoor facilities with sea water. Cross connections may be included for emergencies. Either of the systems furnishes sea water for the indoor laboratory and outdoor test pad.

Toxic materials must be kept out of the culture water. Using metals in the pumping and tank system must be avoided. Insecticides and volatile petroleum products are lethal to lobsters. These products must not exist in the inlet water nor be used in the vicinity of the culture tanks (Gates et al. 1974).

Optimum salinity for the cultures varies between 30 and 31 parts per thousand. Water from Long Island Sound approximates this ratio. When high percentages of recycled water are used, salinity should be monitored to avoid increases caused by evaporation.

Gates et al. (1974) recommend a minimum oxygen level of 6.4 milligrams per liter (5.34×10^{-5} lb/gal). Removal of biodeposits and uneaten food eliminates oxygen sinks. Sediments remove about three times the amount of oxygen used by the lobsters. Maintaining proper combinations of open-system water flow, aeration, and recirculation will prevent suffocating the lobsters. Gates et al. (1974) report that, even with proper aeration, filtration, and recirculation, the culture water for lobsters needs to be renewed every two or three weeks.

Figure 24 from McLeese (1956) portrays the lethal and tolerance zones for lobsters as defined by culture water temperature, salinity, and dissolved oxygen content.

WATER SUPPLIES

Two 200-millimeter (8-in) high-density polyethylene pipes supply fresh ambient sea water through coarse screen intakes located off the inlet canal jetty. Either supplies the facility requirements, thus allowing maintenance of one without interrupting service of the other. Eight 2.2-kilowatt (3-hp) pumps (four in each main water system) permit flexible pumping of fresh sea water, recycled water from the biological filter discharge, or power-plant effluent from a storage tank.

Pressure in the power plant discharge line maintains the effluent in the storage tank head at 6.7-meter (22-ft) elevation. (Note that since power plant discharge pressure is not known at this time, variation from preliminary figures could alter the facility design and operation.) The effluent storage tank buffers sudden pressure changes from shifts in operation, and also allows a short time lag for turning off the heat pump in the event of a power-plant shut down. Overflow from the effluent storage tank discharges into the adjacent drain channel. The incoming pipe limits the effluent supply to a maximum of 50,000 liters per minute (13,200 gal/min). The maximum temperature increase to the power-plant cooling water thus is restricted to .25°C (.45°F). Effluent sea-water level in the storage tank permits gravity flow to the heat exchanger channels, seaweed-culture ponds, and biological filters, if desired. Siphon action provides flow to the heat pump.

Figure 25 illustrates pump and head systems. Water from the main pumps goes to head tanks located on the second floor of the mechanical equipment area. The continuous backflushing microscreens installed in the two main head tanks may be bypassed if filtered water is not desired. The main head tanks are used as settling chambers. They supply sea water for all other sea-water systems.

HEAD TANKS

Two head tanks facilitate the heat exchanger system--one for water entering the heat exchanger and the other for heated water returning from the heat exchanger. At high flows, independent heads run the water in the tanks to permit passive gravity flow through the heat exchanger. At low flows a small pump circulates sea water through the heat exchanger elements and interconnected head tanks.

A similar head-tank system supplies culture water flow to the heat pump. Sea water for the primary tanks comes through a one-way valve from the secondary heat exchanger tank if sufficient heat-exchanger water is available. A float-controlled valve from the main head tank supplies additional water when necessary. When needed, a pump circulates water to the heat pump at either high or very low flow.

The two main sea-water systems use separate head tanks for both the heat exchangers and the heat pump. A single tank supplies power-plant effluent to the sea-water laboratory when the main plumbing system does not use effluent.

All of the head tanks may draw water from the main pumps and have substantial overflow pipes, which prevent spills into the mechanical equipment below. Compressed air, available at all head tanks, desorbs supersaturated, heated sea water.

Each of the two pilot-scale subsystems at the facility receives sea water through three 100-millimeter (4-in) plastic distribution pipes with a combined capacity of 2800 liters per minute (740 gal/min). Pipes run through a drainage culvert that connects the service pits along major plumbing routes. This accommodates cleaning and installation of additional plumbing in the future. See Figures 26 through 30.

The indoor sea-water laboratory and outdoor test pad have a sea-water flow of 1000 liters per minute (264 gal/min) through four 55-millimeter (2-in) polyvinylchloride pipes. Electrical connections in the laboratory are located above the overhead sea-water plumbing.

TABLE 8 *Pilot plant construction cost estimates*

Earth removal	26,000
Building construction	122,000
Septic system	3,000
Fresh water supply system	2,000
Electrical supply (250 kw)	15,000
Electrical control system	17,000
Alarm system	7,000
Freezers	2,000
Sea water pumps (10-3 hp and 4-1.5 hp)	12,000
Air compressors (2-25 hp)	16,000
Oil furnace (200 hp)	36,000
Oil tank (5,000 gal)	6,000
Micro screens (2-600 GPM; 50 μm)	54,000
Heat storage tank (10,000 gal)	15,000
Heat pump and associated equipment	120,000
Head tanks	20,000
Effluent storage tank (10,000 gal)	15,000
Heat exchanger channels	16,000
Heat exchanger elements	10,000
Biological filters	26,000
Seaweed ponds	20,000
Lobster raceways	16,000
Sedimentation pond	3,000
Nutrient storage tank	2,000
Greenhouse structures	45,000
Plumbing	
Power plant effluent pipe	6,000
Intake lines and screens	12,000
Plumbing service pits	30,000
Drain lines	24,000
Distribution lines	28,000
Fittings and valves	50,000
Drain channel	20,000
Back filling	17,000
Blacktop	15,000
Crushed rock paths	12,000
Landscaping	10,000
Vehicles	15,000
Raceway service unit	10,000
Dry lab equipment	30,000
Office equipment	10,000
Contingency (50%)	483,000
TOTAL	$1,398,000

THE TOTAL SYSTEM

In the proposed facility, the flexible sea-water supply system serves both the major built-in components and the indoor and outdoor laboratory areas. Both open-system and closed-system cultures can be researched. Series operation or independent operation of major components is possible. The flexible heating system permits simultaneous use of a variety of culture water temperatures. The heating system allows substantial scale testing of alternative technical systems.

The basic biological and technological knowledge required for mariculture is still in its infancy. System requirements are poorly defined. While this underscores the need for the research facility, it also greatly complicates the design process. Flexible mechanical systems accommodate a variety of uses which cannot be predetermined yet. The complexity of the resulting facility and the absence of design precedents make the facility design itself experimental.

The high cost of the pilot-plant facility (Table 8) reflects the overdesign required by lack of knowledge. The rough cost estimates in no way reflect costs for commercial systems where requirements would be well defined and system operation more stable.

Although the proposal does not examine numerous fine details, this preliminary design provides a solid base for further efforts to develop the facility. We suggest reassessing the desired operating capabilities and appropriate system modifications before completing detailed designs and cost estimates. Based on 1976 prices, Table 9 delineates operating costs of the pilot facility.

Projected mass shortages in world food supplies by the turn of the century encourage development of aquatic cultures using waste heat from thermal effluent. Pilot facilities, such as the one proposed, take a necessary step toward the development of an alternate food supply. The physical plant provides flexible support for a broad scope of biological, environmental, and technical investigations. Results of these investigations will provide development information for commercial ventures. The resulting industry could have a substantial impact on how we use our natural resources in the future.

TABLE 9 *Pilot plant annual operating cost estimates*

A) Full-scale operation

Electricity	
Heat pump	22,550
Sea water pumps	3,500
Air compressor	7,000
Building	1,000
Total electricity	34,050
Oil	2,250
Supplies	5,000
Labor	
Mechanical/electrical engineer	18,000
2 workers	19,000
Total labor	37,000
Maintenance	72,400
Contingency	6,000
TOTAL	$156,700

B) Low-level operation

Electricity	
Heat pump	2,255
Sea water pumps	445
Air compressor	700
Building	1,000
Total electricity	4,400
Oil	2,250
Supplies	2,000
Labor	
1 engineer	18,000
1 worker	9,500
Total labor	27,500
Maintenance	25,000
Contingency	2,000
TOTAL	$63,150

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