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Seaweed Raft and Farm Design in the United States and China

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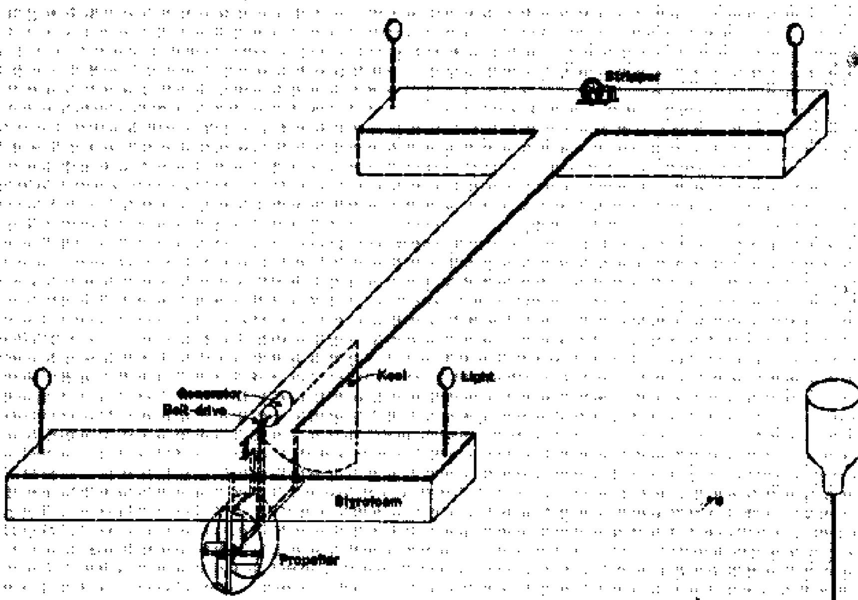

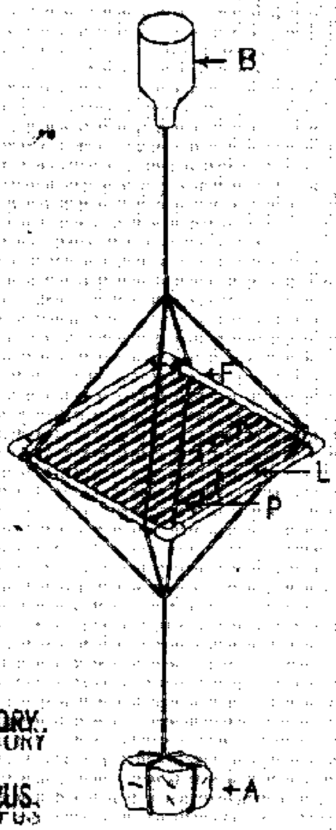

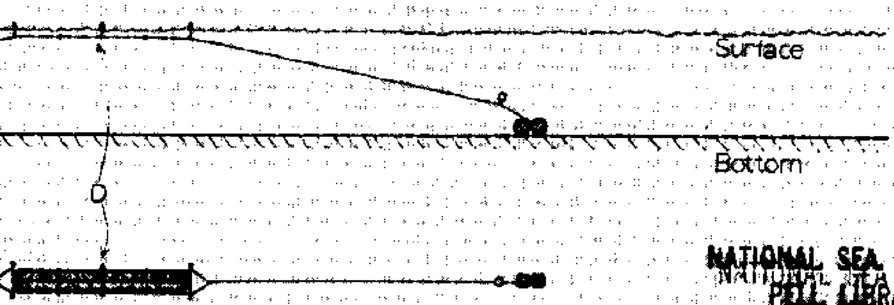

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Edited by Laura B. McKay
New York Sea Grant Institute

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SEAWEED RAFT AND FARM DESIGN IN THE UNITED STATES AND CHINA

Laura B. McKay, Editor
New York Sea Grant Institute
Albany, New York

1983

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PREFACE

Laura B. McKay
New York Sea Grant Institute

Seaweed has long been cultivated in many countries for a variety of purposes, but it is only within the past few years that there has been an interest in cultivating seaweed in the United States. This recent interest has developed in response to at least two of the potential uses for seaweed: food and energy. Seaweed is a mainstay of Oriental diets, and as more and more Americans acquire a taste for these diets and as our Oriental population increases, the demand for seaweed may increase. Using seaweed as biomass for digestion to produce methane gas is a more novel idea which is very attractive because it represents a renewable energy source.

Although seaweed has been used in this country for some time as a source of carageenan (a thickening agent) and agar (a culture medium), it has always been obtained by gathering from the wild. In order to obtain seaweed more efficiently for such larger-scale uses as food and energy, it must be cultivated as a crop. This requires construction of an artificial substrate on which the seaweed can be grown. Seaweed farms have existed in China and Japan for decades, but they are quite new in the United States. As the New York State Marine Biomass Program (methane from seaweed) developed, it became clear that it would be extremely useful for the various scientists who are working on seaweed cultivation across the country to come together to share their insights.

Thus the New York Sea Grant Institute, under the sponsorship of the Gas Research Institute, the New York State Energy Research and Development Authority, the New York Gas Group, and the National Sea Grant College Program, conducted a workshop on seaweed raft and farm design. The workshop was held at the Marine Sciences Research Center, Suny at Stony Brook, Long Island, on May 24-25, 1982, and involved biologists and engineers from the United States and China.

The main objective of the workshop was to develop criteria for the evaluation of seaweed raft or biological test farm designs. These criteria would include both engineering and biological considerations based on the actual field experiences of the seaweed biologists and the general expertise of the marine engineers. Additional goals of the workshop were:

- To provide a forum for engineers and biologists to interact on the subject of seaweed raft and farm design

- To gain an appreciation of how better to involve engineers in the design of seaweed farming structures

- To create a listing of biological facts about seaweed cultivation which must be considered by engineers in designing rafts or farms

- To create a listing of engineering design factors which must be considered by biologists in developing a cultivation system

Participants for the workshop were selected jointly by the sponsors. To help achieve the goals of the workshop, biologists who have "hands on" experience with the culture of seaweeds were invited. Engineers with such experience could not be identified; therefore a group of engineers with more general marine structure design experience were invited. The papers presented at the workshop were also solicited jointly by the sponsors.

The workshop consisted of three sessions. The first involved brief presentations of the current status of seaweed cultivation in China, California, Washington, Florida, South Carolina, and New York. The presentations were followed by a visit to the SUNY Flax Pond Laboratory where *Laminaria*, *Gracilaria*, *Codium*, and *Fucus* were being cultured in tanks. For the second session, participants were randomly divided into two working groups; each group independently developed preliminary design evaluation criteria, and then the two groups reconvened to discuss results. For the final session, the group was divided into biologists and engineers; each group then elaborated and refined the design evaluation criteria.

Laura B. McKay
New York Sea Grant Institute

Participants at the Workshop

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WASHINGTON

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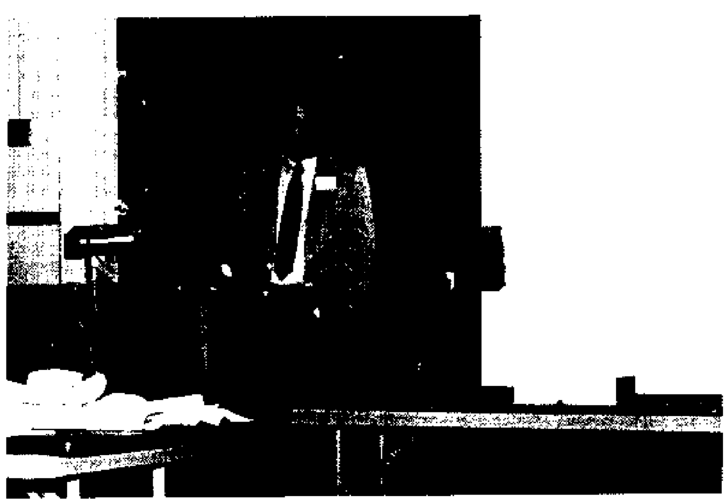

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1

PILOT-SCALE MARICULTURE OF SEAWEEDS IN WASHINGTON

Thomas F. Mumford, Jr., and Donald J. Melvin
Department of Natural Resources, Olympia, Washington

Introduction

Since 1976, with funding from the Department of Natural Resources, the Washington Sea Grant Program, and the Pacific Northwest Regional Commission, we have been conducting research whose ultimate aim is to establish a commercially viable seaweed aquaculture industry in Washington marine waters.

The research was initially to develop technology for the culture of *Iridaea* and *Gigartina* on artificial substrates for the production of carrageenan. The results of this work have been described in a series of papers (Waaland 1973, 1974, 1981; Mumford 1977, 1978, 1979a,b; Mumford and Waaland 1980; Davis 1980). Initial techniques were devised by Waaland at the University of Washington, described in his paper in this symposium, and then scaled up to pilot-scale operations at the Department of Natural Resources laboratory. The seeding of these two species of carrageenophytes was successfully performed on nets, the seeded nets outplanted, and the plants grown to maturity. However, fouling and lack of nutrients caused poor growth at the two main test sites in Puget Sound. At the same time, an economic analysis (Conte and Mumford 1980) showed that the cost of production was about $4,000 per dry metric ton. Although it was felt that this cost could have been lowered to the market price of comparable carrageenophytes (*Chondrus* and *Iridaea* from Chile) at the beginning of the project ($1,000 to $1,200 per metric ton), the success of *Eucheuma* production in the Philippines lowered the competitive price of carrageenophytes to $200 to $400 per metric ton, a price with which our technology could not compete.

As many of the structures used for the *Iridaea*/*Gigartina* project were designed with the idea that they could be used in the future for nori culture, the project in 1980 deemphasized *Iridaea*/*Gigartina* cultivation and most of the effort since went into *Porphyra* cultivation. Preliminary investigations (Merrill 1981) showed that indeed the culture of *Porphyra* using Japanese technology was very likely feasible in Washington, and that many sites in Puget Sound were suited for culture. A Japanese consultant assisted in site selection and in design of structures. The necessary equipment has been either constructed or purchased to operate a 70 to 100 net size demonstration farm. A market and preliminary economic analysis has been performed for nori farms of various sizes (Kramer, Chin & Mayo, Inc., 1982). At this time (May 1982) the Department of Natural Resources is negotiating for a Japanese consultant to assist in the final design, placement, operation, and design refinement of a pilot farm during the fall and winter of 1982-1983. This farm should demonstrate biological feasibility, allow workers here to learn nori farming techniques, and provide for collection of further data for an economic feasibility analysis of the farm.

This chapter sums up our experience to date with the culture of macroalgae on pilot-scale surface-oriented structures. We shall discuss the technical and philosophical approaches that we have found useful in dealing with a comparatively small-scale raft culture system based largely on the Japanese model.

Seeding

The seeding or placing of propagules on artificial substrates such as nets or ropes can be done with remarkable ease for *Iridaea* and *Gigartina*. The details are given in Mumford and Waaland (1980). This method relies on the even distribution of spores (either tetraspores or carpospores) on netting. Rope and twine was also seeded with equal ease. Spore density can be controlled, and viability appeared to be high (more than 80%).

In this instance, the set was done at one time. All the necessary spores were put on in one application.

With the Japanese method for seeding nets with conchospores (see Figure 1.1 for *Porphyra*'s life cycle) to produce the blade phase of *Porphyra*, the nets are not seeded with the final density of spores needed. After the initial set with conchospores liberated from conchocelis-bearing shells (the carpospores actually bore into shells and grow into the conchocelis phase), the nets are grown for about 4 to 6 weeks during which time the small bladelets produce monospores, an asexual mode of reproduction, to give a staggered number of age classes of blades on the nets. During the formation and reseeding of nets with monospores, spores from genetically different but adjacent nets can cross-contaminate nets.

The genetic uniformity of propagules is important in maintaining strains for genetic work (Barilotti 1980; Neushul 1981). The use of naturally produced propagules from wild plants will not give genetically uniform offspring.

In the culture of *Porphyra*, carpospores from blades can be used to inoculate shells. This will not give a genetically consistent annual inoculation as will the use of unialgal cultures of conchocelis (tetrasporophyte). The free-living form of conchocelis from laboratory cultures is homogenized in a blender and used for inoculum.

If it is assumed that meiosis occurs during the formation of conchospores, even with a genetically uniform diploid conchocelis culture, the haploid conchospores will not be genetically uniform.

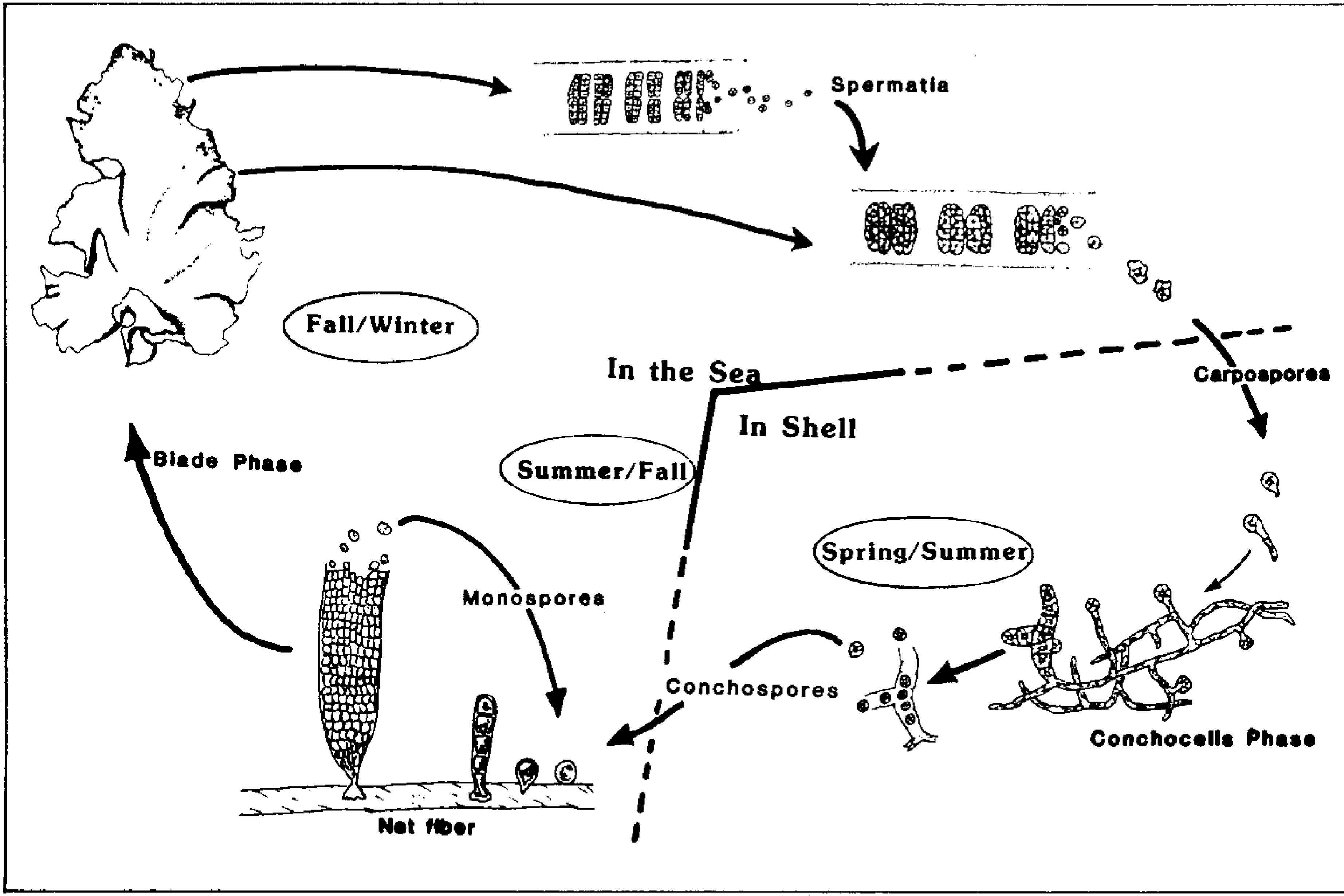


FIGURE 1.1 Life Cycle Typical of Species of _Porphyra_ Used for Commercial Production of Nori

Use of vegetative propagules from the haploid blade phase for seeding of nets can overcome this problem (see Waaland, Chapter 2, this volume; Sylvester and Waaland, in press).

Outplanting

Once the seeding or inoculation of the substrate has taken place, the germlings must survive to maturity. This may require that the nets be placed in a "greenhouse" where they are grown to a certain size before outplanting to the field. This ensures that competition from fouling organisms is minimized, or that the plants are large enough to outcompete them when put in the field.

The growth requirements for the spores and/or germling phase may be different from the adult plants; this must be determined for each species (Neushul 1981).

Timing of the outplanting to the field may be critical (Rosenberg and Ramus 1981). The presence of spores from fouling organisms should be monitored and the outplanting should take place at a time when the presence of spores is minimal. For instance, there are usually spring and fall blooms of diatoms in Washington, and outplanting at these times should be avoided.

As with the outplanting of higher plants, consideration should be given to hardening the germlings before outplanting. This may involve adapting the plants to higher light intensities, or different temperature or nutrient regimes.

The method of transportation of the seeded substrate to the field should avoid any shock to the plants. Photosynthesis may be reduced to a small fraction of the normal amount by handling and transportation. Recovery may take weeks. For example, Japanese nori farmers believe that changing only one-third of the conchocelis culture media at one time, avoids shocking the plants and enables them to grow faster (Miura, personal communication).

Structures

Initial structures used for the field culture of *Iridaea* and *Gigartina* were bottom oriented to mimic the natural environment of the plants, and to minimize visual impacts and vandalism. The placement and the merits of these types of structures are discussed in Mumford and Waaland (1980). Schematics of the structures are given in Figure 1.2 and costs of materials and labor in Table 1.1.

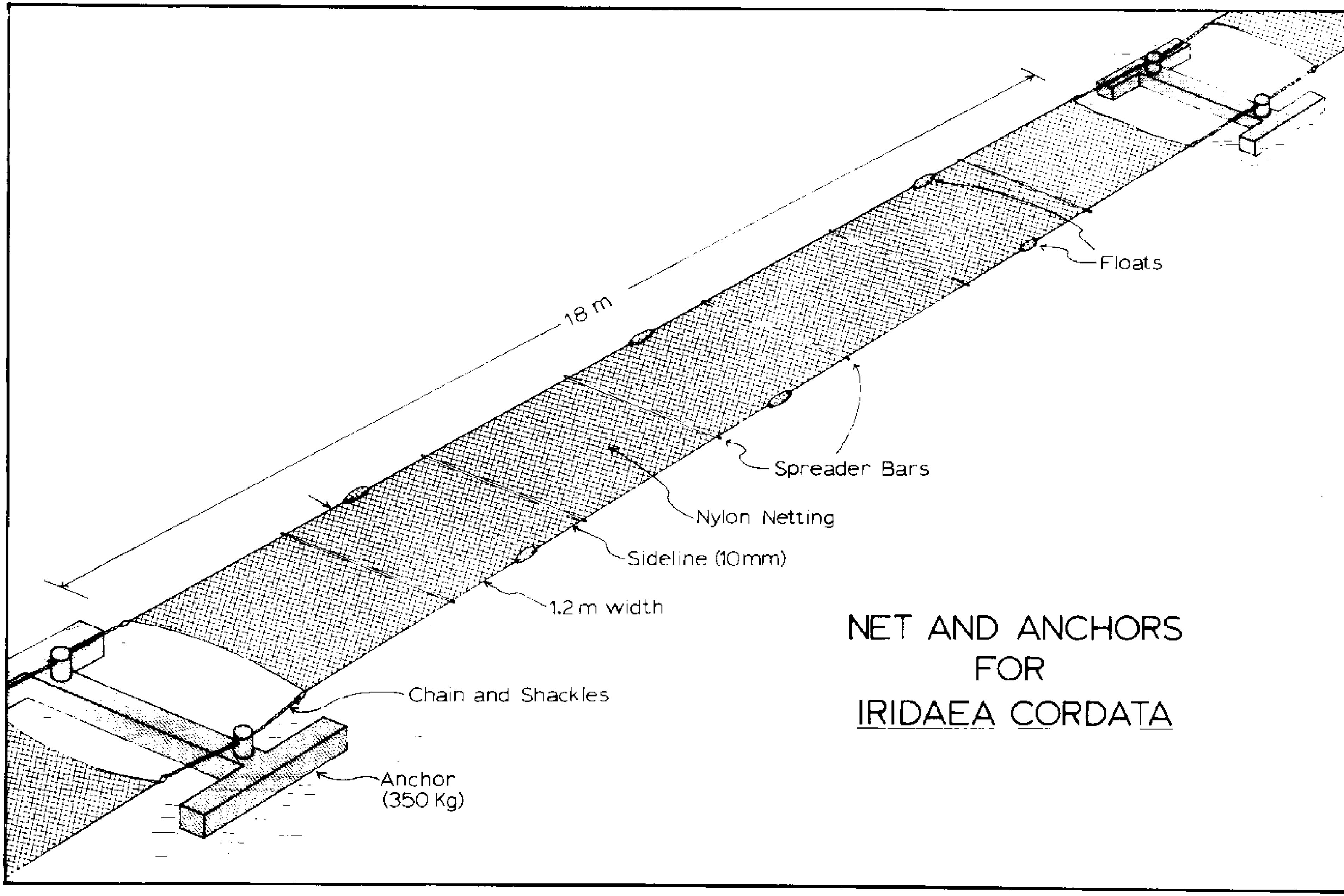


FIGURE 1.2 "H" Anchor and Bottom Nets (from Mumford 1979a)

TABLE 1.1 Types of Anchors and Frames

Type	Costs ($)				
	Materials		Labor		Total
	Anchor	Nets	Construction	Placement	
Barrel	$102	$90	$3	Most costly	$195
Fluke	22	90	29	Moderate	$141
Pipe	4	90	9	Least	$103

Bottom culture: one net per frame at $48/net (custom made in Seattle)

Surface culture: 6 nets/frame at $15/net (hibi from Japan)
6 barrels, 2 flukes, or 2 pipe anchors per frame

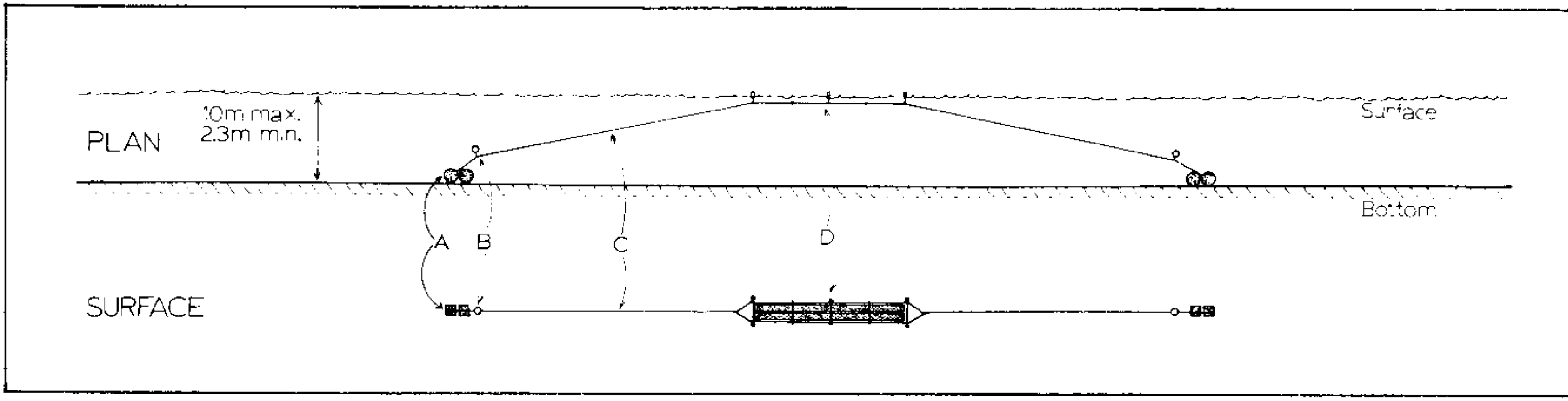
When we found that bottom-oriented structures required critical placement of the anchors, were subject to fouling, and contributed to poor growth, surface-oriented structures were built and placed at two sites in southern Puget Sound. All these structures, top and bottom, were designed for uniform-size nets used in the nori industry, called "hibi." These nets are a standard 18 x 1.5 meters (1.2 meters until 1978). While our type of surface net frame design has not changed appreciably during the past few years (Figure 1.3), the types of anchors have. At first, because of the availability of used metal garbage cans as forms, we used these filled with concrete and in bundles of one, two, and finally three as anchors. These structures, while exciting to place, were cumbersome and tended to drag in currents or roll down steeply inclined bottoms. We are now using either fluke-type anchors (Figure 1.4) or pipe anchors (Figure 1.5) (Takahashi 1972).

Anchors should be designed so that their placement can be "sloppy," that is, not critical, and the attachment of structures can be made easily. It should be possible to make any adjustment needed because of misplacement from the surface. As with any commercial aquaculture operation, the use of divers should be avoided.

An important point in all structures is to assure that all rigid portions such as spreader bars are lashed tightly to ropes. This prevents chafing and allows only flexing of ropes. In Japanese structures there are very few metal or plastic fastening devices; rope or twine is used almost exclusively.

Sites

Site criteria for the placement of growing structures must be carefully analyzed before any test structures are placed. The criteria that should be examined are given in Table 1.2. This is a checklist given to potential nori farmers to fill out in preparation for consideration of an aquaculture site. It is very important to examine the seasonality of the changes. The



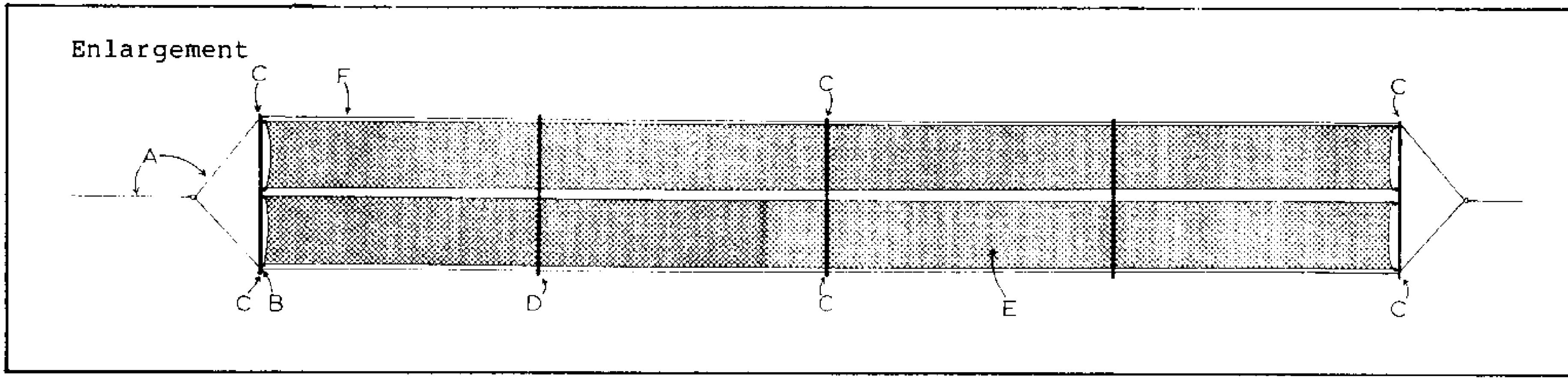


FIGURE 1.3 Production Framework

This framework holds six nets at or near the surface.
Total dimensions: 228' x 11'
All lines: 3/8" polypropylene rope
Spreaders: 16 PVC (Class 200) pipe crossbars capped at both ends (14 @ 1.25"; 2 @ 2")
Material costs: $64.03
Construction time: 12 man-hours
Construction costs: $120.00 @ $10/hr
Total cost per framework: $184.03
"Topper" floats (foam-injected tires) are placed at each end ($8.45 ea.)

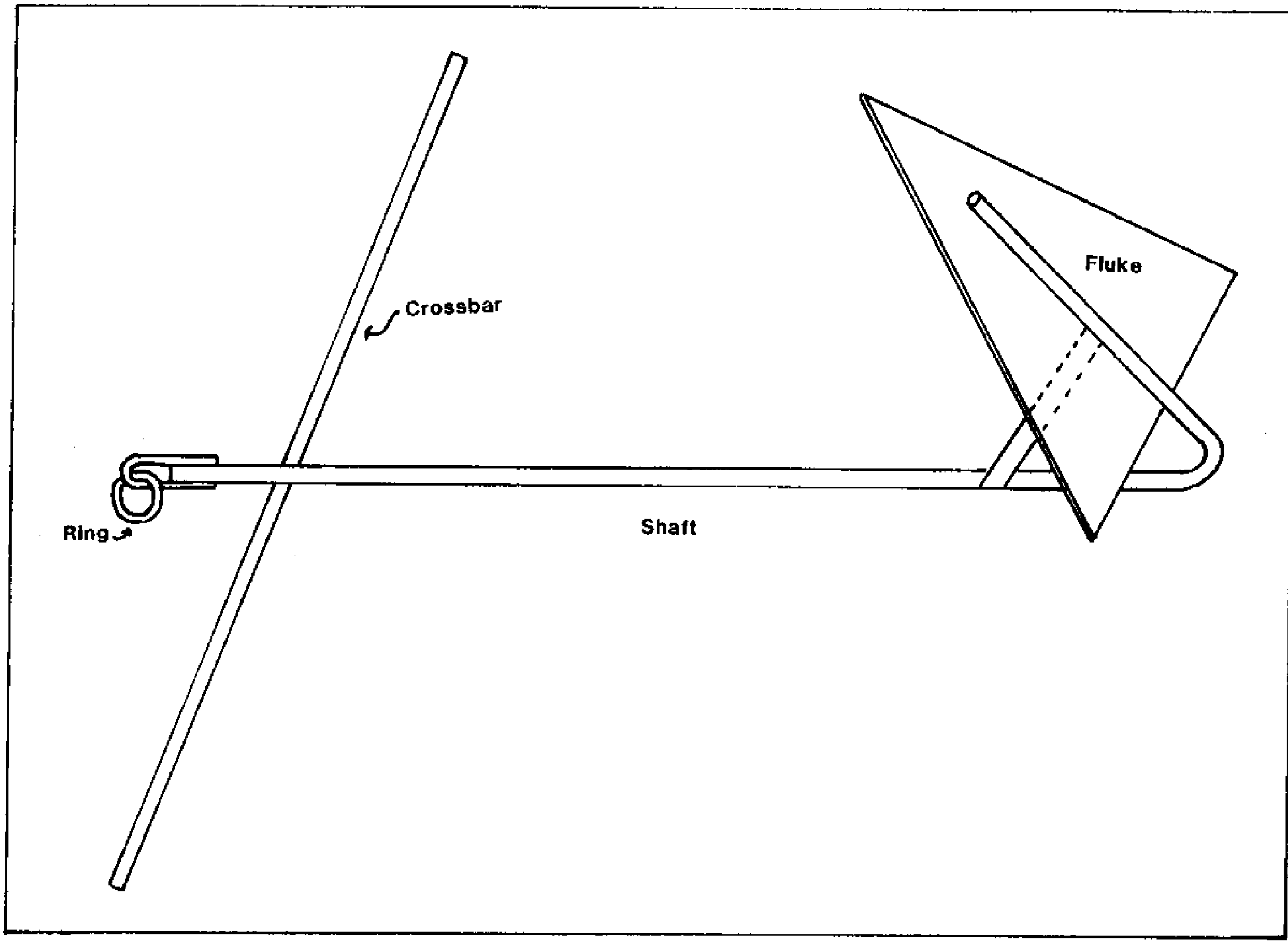


FIGURE 1.4 Fluke Anchor

Materials:

Shaft: 1" (25 mm) steel rod ("rebar"), 6' (183 cm) long
Crossbar: 1" (25 mm) steel rod, 5' (152 cm) long
Fluke: 28" (71 cm) x 22" (50 cm) x 0.25" (6 mm) steel plate
Fluke at approx. 40o to shaft, with reinforcing strut
Ring: 0.75" x 6" steel made from car coil springs

Material costs: $21.98
Labor costs: $28.88
Total costs: $50.86

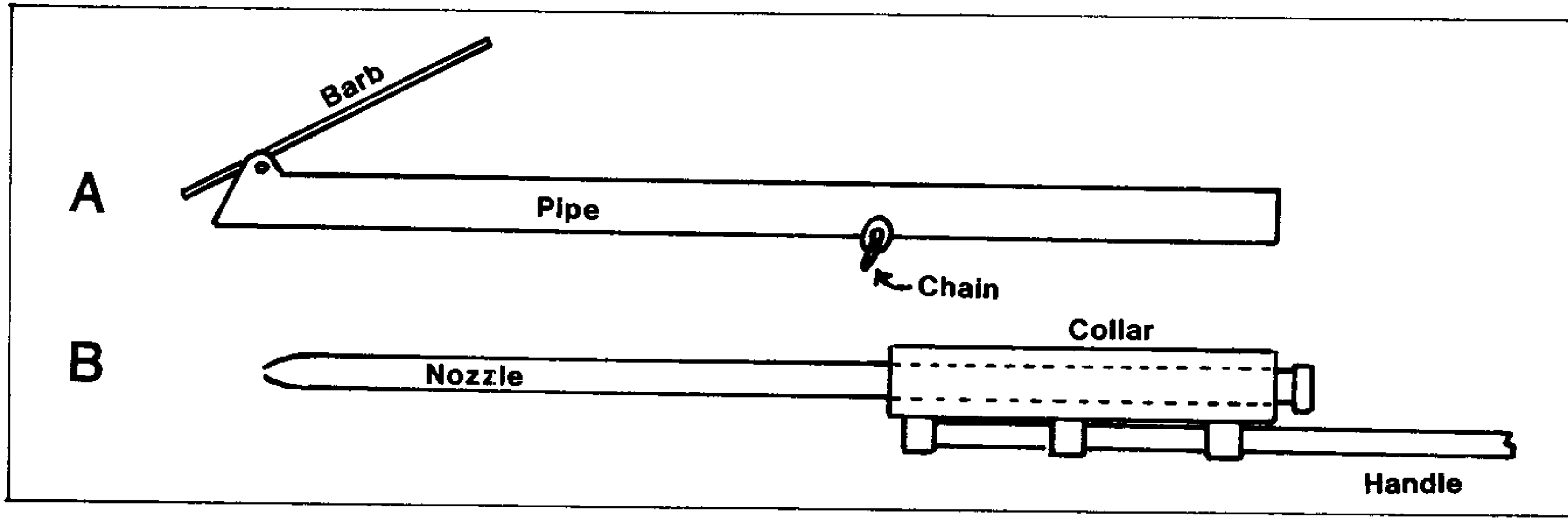


FIGURE 1.5 Pipe Anchor

Materials:

A Anchor:

Pipe:	2" diam steel pipe 52" long, open at both ends
Barb:	17" x 2" x 3/8" flat stock, folded flat against shaft during insertion, angles out when pulled up
Chain:	2 links of 2" chain welded about 1/3 of distance from top; anchor line attached here
Hinge:	1/2" bar welded between two flaps cut and bent out from pipe shaft and 3/4" piece of pipe welded to barb

B Inserter

Nozzle:	1.5" diam. pipe 52" long, necked down to hole with 1.5" hose coupling on upper end
Collar:	3" pipe open at bottom end, closed and welded to nozzle at upper end
Handles:	1.5" aluminumrods in 12' sections attached to collar

Materials cost:	$4.40
Labor costs:	$9.00 ea. @ $20/hr
Total cost:	$13.40

TABLE 1.2 Checklist for Nori Cultivation Site Criteria

A. Water (surface and/or bottom)
   1. Salinity (ppt)
      ________min(________month); ________max(________month)
   2. Temperature (^{o}C or F)
      ________min(________month); ________max(________month)
   3. Nutrients (mg/l or ug at/l)
      a. Nitrate
         ________min(________month); ________max(________month)
      b. Ammonia
         ________min(________month); ________max(________month)
      c. Phosphate
         ________min(________month); ________max(________month)
   4. pH
      ________min(________month); ________max(________month)
   5. Debris
      a. Eelgrass
      b. Logs
      c. Floating kelp
   6. Currents
      a. Velocity
         ________knots incoming, ________knots outgoing
      b. Direction
         ________^{o} incoming, ________^{o} outgoing
      c. Changes with lunar cycle
   7. Types of plankton present
   8. Bottom type for anchoring
   9. Bottom depth
      ________min; ________max

B. Climatological
   1. Light
      a. Incident radiation (langleys or einsteins)
      b. Sunny days vs. overcast
      c. Secchi disc reading (for light penetration)
   2. Relative humidity (fog pattern)
   3. Air temperature (^{o}C or F)
      ________min(________month); ________max(________month)
   4. Wind
      a. Direction
      b. Velocity (knots or cm/sec)
         ________min(________month); ________max(________month)
      c. Seasonal changes
   5. Wave height (fetch) (ft or m)
      ________min(________month); ________max(________month)

C. Institutional
   1. Permits
      a. Shoreline Management Act (________County)
      b. Army Corps of Engineers
      c. Others
   2. Shore access (ramp, dock)
      a. distance
         (________miles/km)

   b. Facility available on upland
3. Upland ownership (see county assessor/auditor)
4. Tideland ownership (see Dept. of Natural Resources or county)
5. Conflicting water uses (see DNR or Dept. of Ecology Marine Atlas)
6. Shoreline Management Act zoning for upland (see county planners)

predictability of these values and their seasonal changes will influence the success of the culture.

Growth

It became obvious from the growth of *Iridaea* and *Gigartina* that the conditions at the surface (above the pycnocline) were considerably different from those near the bottom. Plants at the surface began growth earlier in the season, grew faster, but then suffered from bleaching, necrosis, and eventually were overcome by fouling organisms. Plants on the bottom structures were apparently below the thermocline (Mumford, unpublished data). It was not clear if high light intensity, high temperature, nutrient depletion, or a combination of these factors caused the mortality of the plants at the surface.

Tidal current and wave motion are both important in reducing the static surface boundary layer (Neish and Knutson 1979). Surface structures should therefore be designed to take advantage of any current or wave motion to increase nutrient and gas exchange. In particular, the plants should be attached to a rigid substrate and not allowed to move with the waves.

As an example, *Porphyra* culture using the pole method has undergone a recent change in the Ariake Sea of Japan. The poles have traditionally been bamboo, which is stiff, cheap, and lasts several years. However, these are being replaced by a fiberglass pole that is more expensive but lasts longer so that the cost per year is about the same as for bamboo. However, the fiberglass is more flexible and whips in the wind. This whipping motion moves the nets tied to the poles up and down and gives better growth. This seemingly minor difference can be important in closely packed culture areas.

In areas of very high wave energy, however, consideration must be made of the effects of whiplash and abrasion on the attached plants. Plants attached to a rigid structure or raft will be much more prone to abrasion effects than those on a flexible rope longline or raft.

It is obvious in any culture area that there is a need for a quick feedback information system about environmental and disease conditions that would enable the culturist to adjust net density, or harvest timing, and so on. The closer the system is being run to its maximum density, the more critical the need for the ability to make quick adjustments. Accurate weather predictions would also enable the culturist to make adjustments ahead of time.

Any large-scale aquaculture operation should carefully consider the problems associated with overcrowding. The Japanese have found overcrowding in many areas (such as Matsushima Bay) to result in catastrophic crop failures because of (1) reduced water movement (both tidal current and wave); (2) nutrient depletion; or (3) disease spreading, probably resulting from stressed plants as well as close proximity of a large prey population.

In many of the nets in our experiments, edge effects, whereby plants on the edges of the structure grow better than those toward the center, were very evident. These effects must be carefully considered in any large-scale structure.

Frond area index (FAI) has been considered by Adams and Austin (1979) and Mumford and Waaland (1980) and is clearly important in limiting growth (Evans 1972).

Adams and Austin (1979) and a variety of Japanese workers (see Yoshihara 1977) found that yield remains fairly constant over a wide range of densities of plants on a net or rope (Curve 1 in Figure 1.6). This gives a fairly wide range or window of densities. However, if the plants are stressed from overcrowding of nets, or from a few days of cloudy weather, the curve may be more peaked (Curve 2). Or, if there is a disease problem, the curve may have a critical density beyond which the population may crash (Curve 3).

Harvesting

Harvesting must optimize the yield of the final product in relation to the cost of harvesting. It must be determined whether to make a single harvest on a "throw-away" substrate or structure, or to make multiple harvests on a more permanent structure. If multiple harvests are performed, the harvest interval and the number of harvests must be optimized (Katada and Satomi 1975). The method and place of cutting the plants should allow rapid regrowth. The location of the internal nutrient storage product if used in regrowth, meristematic regions and potential for meristematic growth, and area left for nutrient uptake and photosynthesis must be determined (Wu et al. 1981). Harvesting or cropping can also be used to prevent reproduction in some plants, and hence all growth is put into vegetative tissue.

One-time or "throw-away" harvesting and structures should be considered if fouling over a long term is a problem (as it was with our *Iridaea* culture) or if harvesting costs are very high.

Figure 1.7 shows a logarithmic-type growth curve. It is obvious that the initial foot of the curve should be as short as possible, and that the straight-line portion (growth rate) should

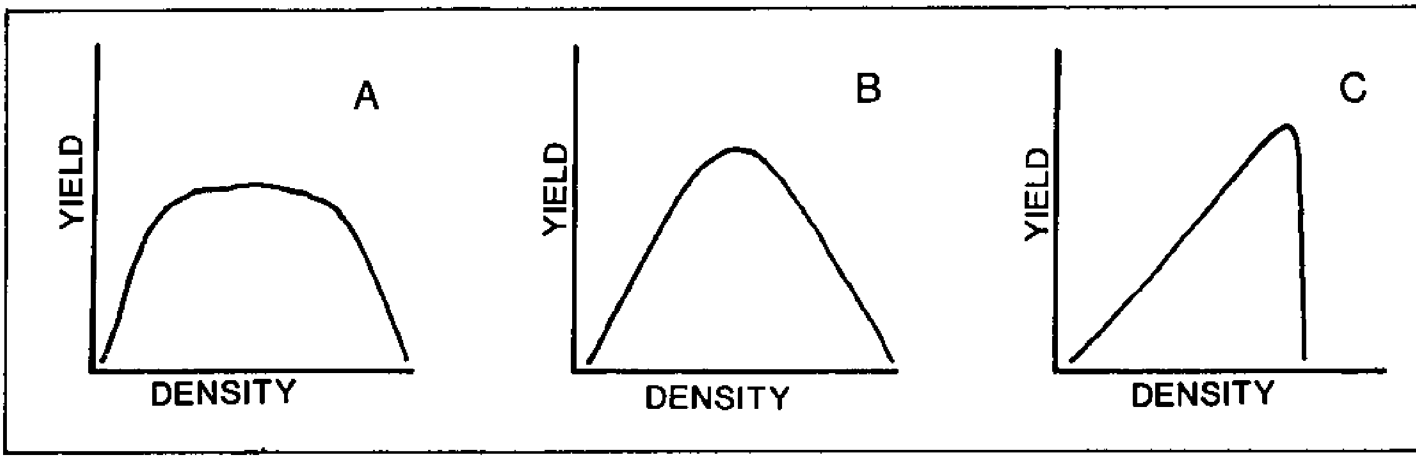


FIGURE 1.6 Yield versus Density Curves

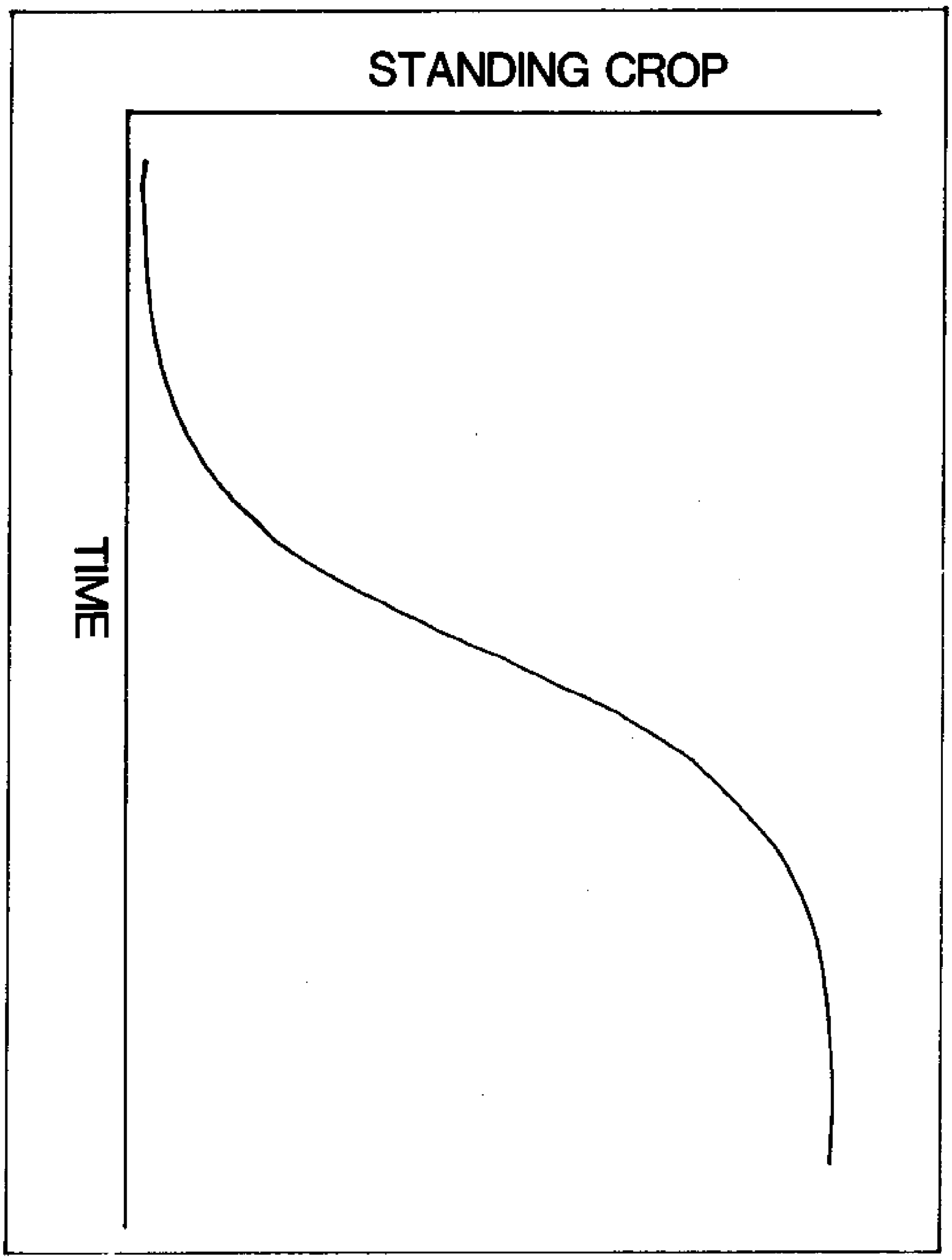


FIGURE 1.7 Hypothetical Standing Crop versus Time Curve for Macroalgae

have as steep a slope as possible. The shortening of the "foot" can be accomplished by not stressing the plant or traumatizing it by rapid changes in its environment during transplantation. The degree of shade or light adaptation of large canopy blades versus the understory blades or portions of the plant left after harvesting should be determined. The exposure of shade-adapted blades to full sunlight after canopy removal may traumatize the plants; this can be avoided by "rotating" the plant's position somehow so that it receives an average light intensity. This is done in tank culture by agitation and movement of the plants (Neish and Knutson 1979; Simpson et al. 1979).

Fouling

"Something else is always going to grow faster that what you are trying to culture," an old seaweed farmer once lamented. "One man's weed is another's profit," a new marine agronomist has stated. Fouling remains a major problem in any field culture system. Although fouling problems are well documented in tank culture (Enright 1979), they have not been as well addressed in field structures. In our experience, fouling by competitive algae, especially ulvoids, can dramatically lower yield (Mumford and Waaland 1980).

In *Porphyra* culture, the presence of any ulvoid in the sheets of nori reduces the value of the sheets dramatically--it is like a worm in the apple. Two main methods of fouling control are used in *Porphyra* cultivation, dessication and chemical. *Porphyra* is more resistant to dessication than almost any other alga; it can be dried to 10 to 20 percent of its wet weight and survive (Inayoshi, personal communication). The older pole method of cultivation allowed a daily immersion period. As raft culture became more common and the nets could not be dried, other means of preventing or killing fouling were devised. The story goes (Miura, personal communication) that a group of nori farmers at Futtsu City in Tokyo Bay tried a variety of common substances and found "Coca-cola" to be effective against ulvoid fouling. Further investigation showed that citric acid was the active ingredient. Now, fouled nets are immersed in a 1 percent solution of citric acid (pH = 1.0-2.0) for 10 to 20 minutes, which kills the ulvoids but not the *Porphyra*.

The type of substrate is important in determining the type of fouling. We have found that kelp species prefer PVC, plastic floats, and "Vexar" mesh to nylon or polypropylene, whereas *Iridaea* and *Gigartina* have the opposite preferences. Whether this is a matter of surface microtopography, chemical interactions, or the hydrophilic or hydrophobic nature of the substrate is not known. Because we have used materials for frames, anchors, and so on that foul with kelp, we have tried painting crossbars and floats with antifouling paint. This is only partially effective, very expensive, and certainly has dubious environmental consequences. Leaching of toxic materials will probably affect adjacent plants.

Timing of outplanting, as mentioned above, should be done to minimize the colonization of new or poorly set substrate. By outplanting only densely set nets with large plants, fouling can often be eliminated. Control of fouling organisms by grazers has also been suggested (Mumford 1979; Gaines 1980). We have used with some success small discs placed around lines which will slide back and forth with each tide change. These tide-driven chafers can reduce fouling significantly.

The Oriental Experience

Seaweeds have been cultivated in the Orient since at least the 1600s. The success of seaweed aquaculture in Japan (Miura 1975) and China (Tseng 1981, 1982) has to be seen to be fully appreciated. The cultural values for edible seaweeds are similar to ours for fine wines, cheeses, and steaks. Seaweeds are photographed with the respect, care, and sophistication of technique we give to alpine flowers.

Many of the advances in cultivation in Japan have been the result of trial and error. However, one must realize that in the case of Porphyra culture this involves over 50,000 people. A high degree of cooperation and sharing of information ensures a remarkably effective system. Research performed by government labs, labs established and funded by nori cooperatives and prefectures, and universities is often done in response to the requests of the farmers. As a result, much of the information flows from the farmer to the researcher, instead of the reverse, as is often the case in the United States. Many of the structures and techniques are the result of millions of man-years of effort in refinement. Increasingly, modern research techniques are being used in strain selection, breeding, effects of pollution, and structure design and analysis.

Some Observations

A research project scaling up to pilot- and then full-scale production should proceed in a slow, orderly fashion. It is very tempting to expand the number of untested structures beyond that which can be monitored, and quickly and easily modified if need be. One should never go beyond one's resources.

Optimizing structures involves a large number of parameters that can be grouped under (1) biological, (2) engineering, and (3) costs. Each of these must be considered, weighed, and constantly reevaluated. The order in which these parameters are approached is probably the most important factor in determining the success of raft culture of macroalgae.

Acknowledgments

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2

EXPERIMENTAL-SCALE RAFT CULTURE OF MARINE MACROALGAE IN INLAND MARINE WATERS

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Introduction

Studies on the form, growth, and productivity of marine macroalgae frequently require that they be grown in habitats where they do not normally occur. This is usually accomplished by growing the plants on some sort of artificial substrate. Often, the plants raised in such experiments must be removed periodically for determination of growth increments or changes in form. The characteristics of the species, the stage at which it is transplanted (i.e., starting with spores or germlings or juvenile plants, or other propagules), how and how frequently it will be measured, and the site used all have a bearing on the design of the culture module and transplant method. The characteristics of the field site will likewise be an important consideration. Bottom characteristics will affect anchoring methods. Tidal amplitude, tidal currents, and wave and storm exposure are important as well.

The purpose of this chapter is to review the design, deployment, and results obtained with small experimental raft modules used for study of transplantation, growth, and production of certain red marine algae which were the subjects of research conducted in the inland waters of Puget Sound and the San Juan Archipelago of Washington State.

Design Criteria

Transplant Module Requirements

The major requirements and limitations for the structures described here were that they be readily constructed using "off the shelf" components locally available, that assembly and deployment be possible by one or two workers using a minimum of specialized tools and gear, that they be transportable in a pickup truck and small boat (less than 5 meters long), and that materials employed in construction be nontoxic, corrosion resistant, and have reasonable durability and longevity (minimum of one full year) in the marine environment. It was also necessary that they be relatively inexpensive. To satisfy these requirements, much of the construction material used was polyvinylchloride pipe (in assorted sizes) for the basic framework, nylon and polypropylene line for rigging, and metal shackles and chain for anchoring. Additional requirements included ease of substrate inoculation starting with either spores or juvenile plants, and in some experiments the possibility of periodically removing and reattaching plants. It was also necessary to be able to recover the entire structure for disposal or reuse upon termination of the experiments.

Most of the structures described here were designed for growth of the red algae *Iridaea cordata* (Turner) Bory and *Gigartina exasperata* Harvey and Bailey. Both of these seaweeds have small (1 centimeter diameter) discoid holdfasts, narrow and short cylindrical stipes, and single or multiple blades (typically 0.5 meter long by 0.15 meter wide, but often as much as 1 meter long). Typical fresh weights of these species ranged from a few grams to as much as 500 grams. In addition to these two species, other genera and species have been grown using these culture modules which are generally suitable for many different species.

Environmental Requirements

The marine environments in which these structures were deployed were the sheltered, inland marine waters of Puget Sound and the San Juan Archipelago of Washington State. These waters are characterized by high tidal amplitude (up to 6 meters), swift tidal currents, considerable mixing, generally high nutrient levels, and modest temperature fluctuations (seasonal range from 8 to 14°C). The waters are often turbid because of plankton communities. Both soft (mud, sand, gravel) and hard (rocky reefs and ledges) bottom areas were used in these experiments; the soft bottom areas are more common. Experiments were conducted in waters less than 15 to 20 meters deep so that the structures, attached plants, and anchors could be inspected by scuba diving. It proved desirable to locate the seaweeds within a few meters of the surface to facilitate access to light in the often turbid waters. Major storms in these waters are seasonal (fall and winter) and their direction is usually predictable. There are numerous islands and inlets in the region and it is possible to choose field sites with modest fetch and minimal wave action.

Environmental Constraints

The areas in which these experiments were conducted are used extensively for recreational boating and commercial and sport fishing. The uplands in many of the shore areas are the sites of permanent or vacation homes. Thus it was essential that the structures be unobtrusive and not interfere with these other activities. In some cases the experiments were conducted in waters adjacent to marine laboratories for security reasons and to minimize potential interactions with these other activities. A further constraint in most of this research was that the travel time from the laboratory to the field sites was a minimum of 4 hours and trips had to be coordinated with ferry schedules.

Typical site visit intervals ranged from once per week to once per month.

Designs Tested

Over the course of over a decade, various culture module designs were employed for various purposes. These fall into three major categories.

Line Modules

Vertically oriented linear arrays supporting numerous plants were used to test survivability and determine growth rates at various depths in early stages of the research (Figure 2.1). These linear modules were anchored with anchor blocks or stones in soft bottom areas and with rock fasteners (pitons) in hard bottom areas. Subsurface floats, nearly exposed at low tide, were used to keep the linear arrays vertical at a constant height above the bottom. A unique feature of these units was the small removable/replaceable holders used to secure juvenile plants to the line (Figure 2.2). These holders permitted periodic removal for weight measurement and photography of specimens. They worked well with these species, which have small holdfasts. Results of experiments using these modules with *I. cordata* and *G. exasperata* can be found in Waaland (1973). The same linear arrays were tested with *Sarcodiotheca gaudichaudii*, but the plants were threaded through braided plastic line. With subsurface floats, it can be difficult to locate the experimental units in turbid waters.

Lengths of line inoculated with spores and arrayed horizontally or vertically were also used for studies of growth versus depth (Figure 2.3). This is a generally useful method and finds very large-scale use with seaweeds such as *Laminaria*, *Undaria*, *Eucheuma*, and *Gracilaria* (Tseng 1981). The lines may be arranged in arrays covering a large surface area. Lines inoculated with *I. cordata* and *G. exasperata* were hung from a raft at various depths below the surface to test growth at various depths (Waaland 1981). A similar method using vertically oriented lines has also been used in bottom-tethered configurations by Adams and Austin (1978). Inoculated lengths of line have been tested as a way to retain holdfasts over winter in tank culture; inoculated line was fastened to neutrally buoyant supports which were maintained in tank culture (Waaland, unpublished).

If a suitable inoculation method is available, this longline culture method is very useful and has widespread applicability. Recent development of an inoculation method for such substrates which does not require the use of spores greatly extends its utility (Sylvester and Waaland, in press).

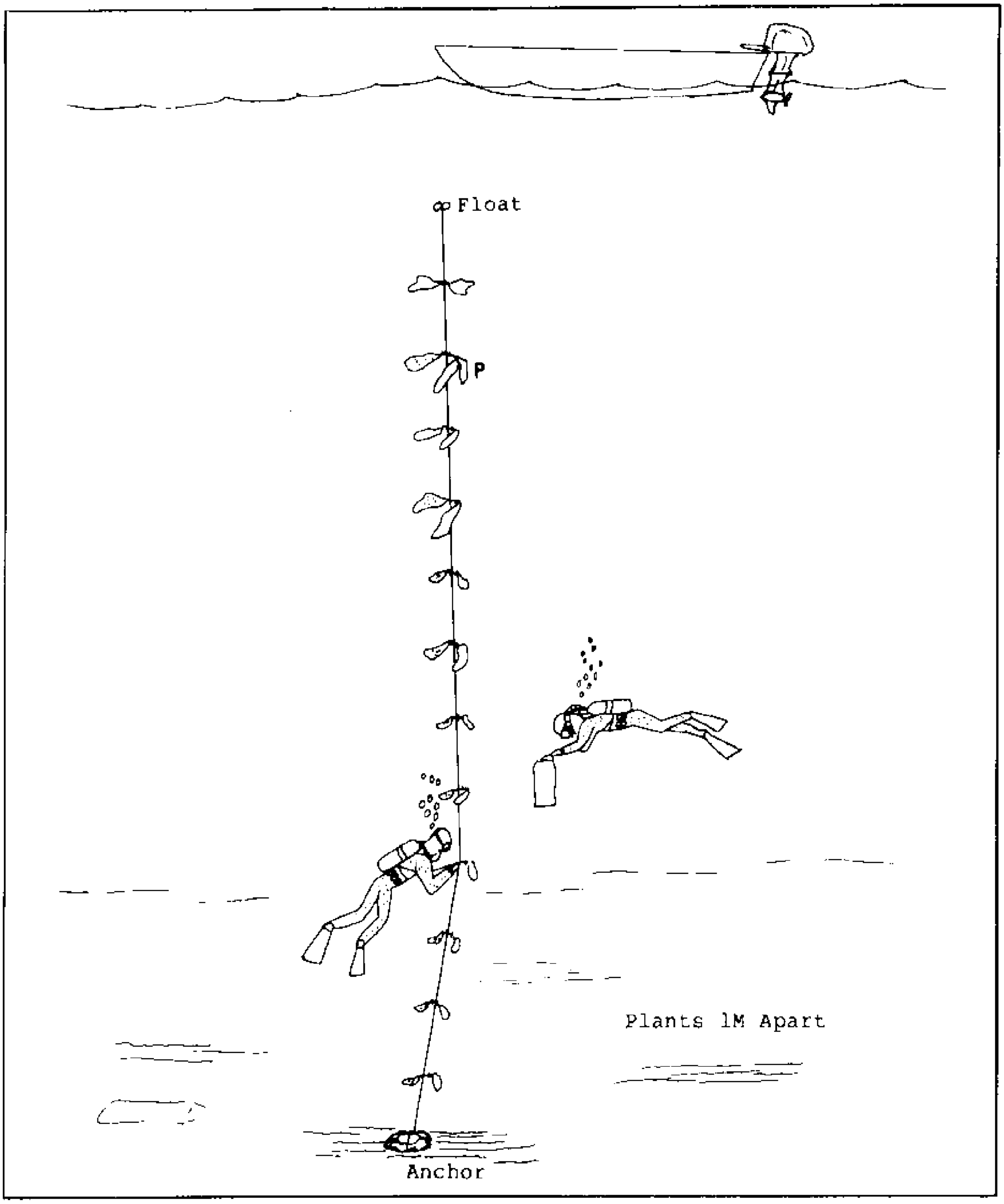

FIGURE 2.1 Linear Module with Vertical Orientation (Plants were fastened at 1-m intervals for testing growth rate versus depth. In use, the unit was anchored to the bottom and the entire line was periodically removed by divers for laboratory measurements of weight and for photographing the plants. The holders illustrated in Figure 2.2 allowed removal of plants for these purposes.)

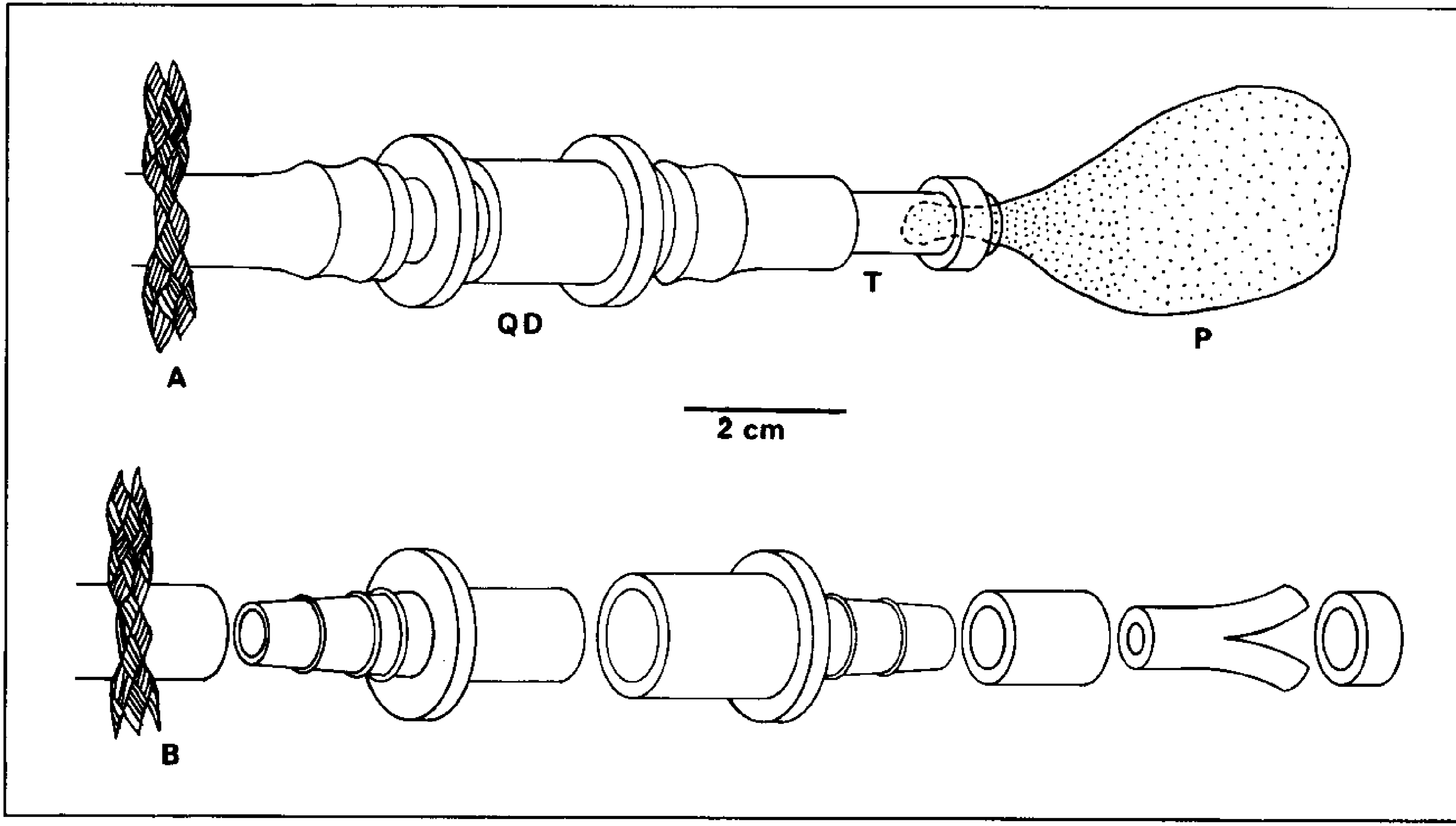

FIGURE 2.2 Removable Holder for Transplanting Individual Plants with Small Holdfasts (A shows assembled view; B shows exploded view. Plants [P] are inserted in transparent tubing [T] which is fastened to a quick disconnect [QD] tubing connector; two such units were joined by tubing inserted through the mooring line.)

FIGURE 2.3 Lengths of Line Inoculated with Spores of *Iridaea cordata* by Exposure of the Line in a Wild Population of *I. cordata* in Late Summer when Spores Were Abundant (These lines were suspended at various depths below the surface by attaching them to hanging lines supported by a raft. Growth rates versus depth were measured in these experiments. Laboratory-seeded lines were also used in some of these experiments. Lines are 0.5 m long.)

Frame Modules

In this category the purpose has usually been to create horizontal arrays of seaweed populations to test growth and yield of populations on a surface area basis. The substrate is usually line or net that has been inoculated with spores, juvenile plants, or vegetative propagules. Typical frame module sizes (dictated by the size that can be handled by one or two persons) are 0.25 x 0.25 m to 1 x 2 m (Figure 2.4). The dimensions of the plastic pipe and nylon net and other rigging used in construction are often a major consideration in determining size. Square or rectangular frames moored tightly or loosely have been used for growth studies and for studies of spore availability and recruitment (Waaland 1974, 1981; Mumford 1977). Spar buoy mooring systems on X-shaped frames (Figure 2.5) minimize rigging in such devices and reduce the surface area available to fouling organisms (Waaland, unpublished).

Frames mounted in tanks have also been used. This permits study of the effects of unidirectional water motion and angle of orientation on growth. Fouling in such experiments was a serious problem not usually encountered in natural habitats.

A particularly useful variation of this basic concept has recently been deployed (Figure 2.6). It is inexpensive, lightweight, simple to construct, and durable. It consists of a surface float from which a frame is suspended; the frame may be rigged with line or net. Depth adjustment and other manipulations are easily carried out.

Floating Enclosures

Floating enclosures of two types have been tested. The first consisted of polyethylene baskets (30 cm wide x 60 cm long x 30 cm deep) with transparent covers (Figure 2.7). These assemblies were suspended from a larger raft so that they were constantly immersed. The only mechanism for providing water and plant motion was tidal current and wave action. No satisfactory mechanism was found for preventing loss of plants that were not firmly tethered to the baskets. No satisfactory growth results were obtained with these units. They are useful for maintaining modest quantities of experimental material when no seawater aquarium facilities are available. It is important to keep plant density low to avoid mutual shading. Allen et al. (1971) have tested similar devices with *Chondrus* and Jones (1959) with *Gracilaria*.

Floating bag modules consisting of plastic pipe rafts supporting plastic bags have been used for growth of *G. exasperata* and *Palmaria palmata* (Figure 2.8) (Davis 1980). A means of pumping water in, an outlet for the overflow (without loss of plants), and a means of circulating water and plants within the bag must be provided. Air-lift pumps provide both water pumping and water circulation. With vigorous water motion, a light framework must be built to keep the bag distended or an arrangement for providing a slight hydrostatic head must be

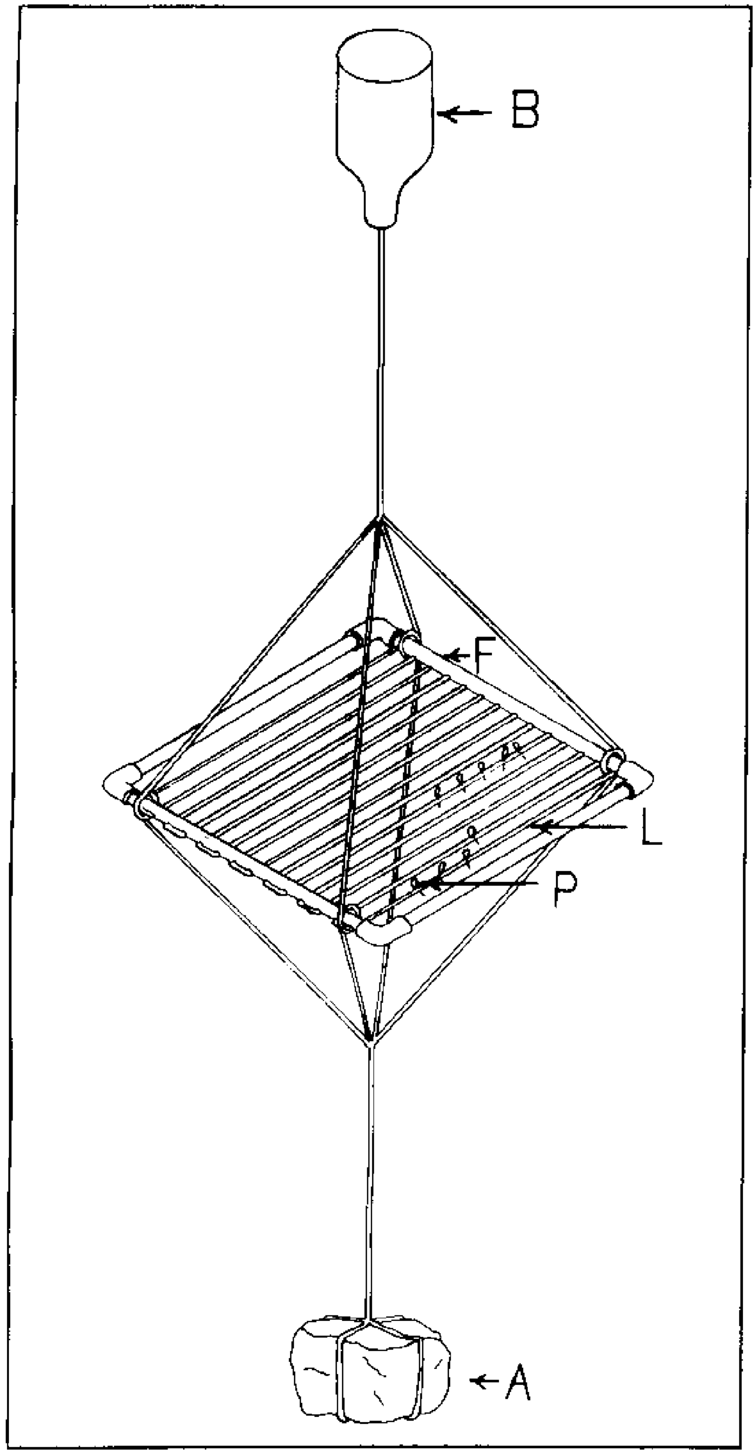

FIGURE 2.4 Square Plastic Pipe Frame (F) Used to Support an Array of Plants (P) Inserted into Line (L) or Net (The entire unit is anchored by an anchor [A] and supported by a subsurface buoy [B] with the rigging shown here. Frames 0.5 x 0.5 m were used in these units.)

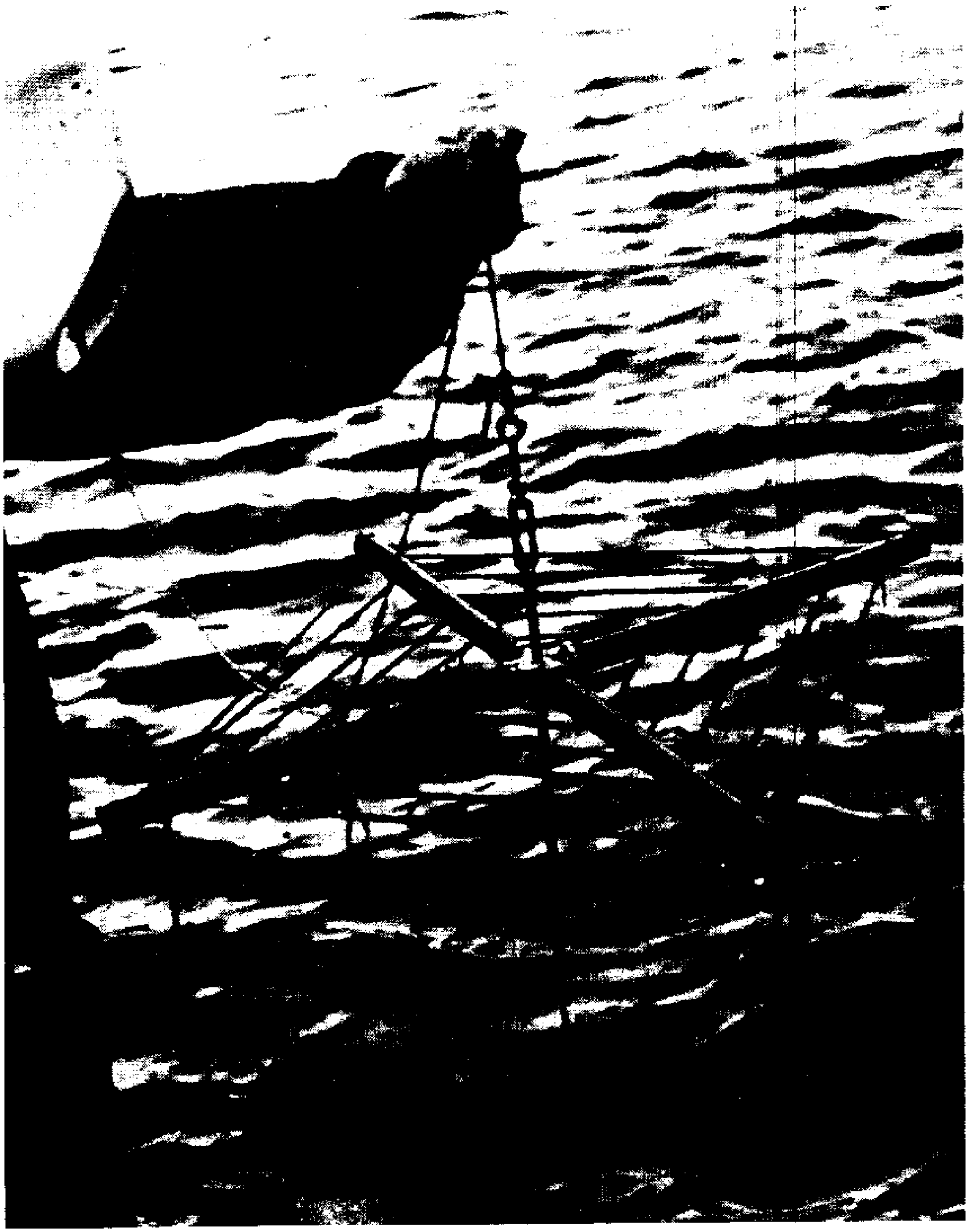

FIGURE 2.5 X-Shaped Plastic Pipe Frame Strung with Spore-Seeded Line for Growth and Yield Studies (The frame was suspended from a stiff rod supported by a surface buoy; a counterweight was used at the bottom of the rod to maintain the frame in a horizontal position in the water. A flexible anchor line tethered the unit to a bottom anchor. This design minimizes the surface area of rigging available for colonization by fouling organisms. The frame is approximately 0.5 x 0.5 m in surface area.)

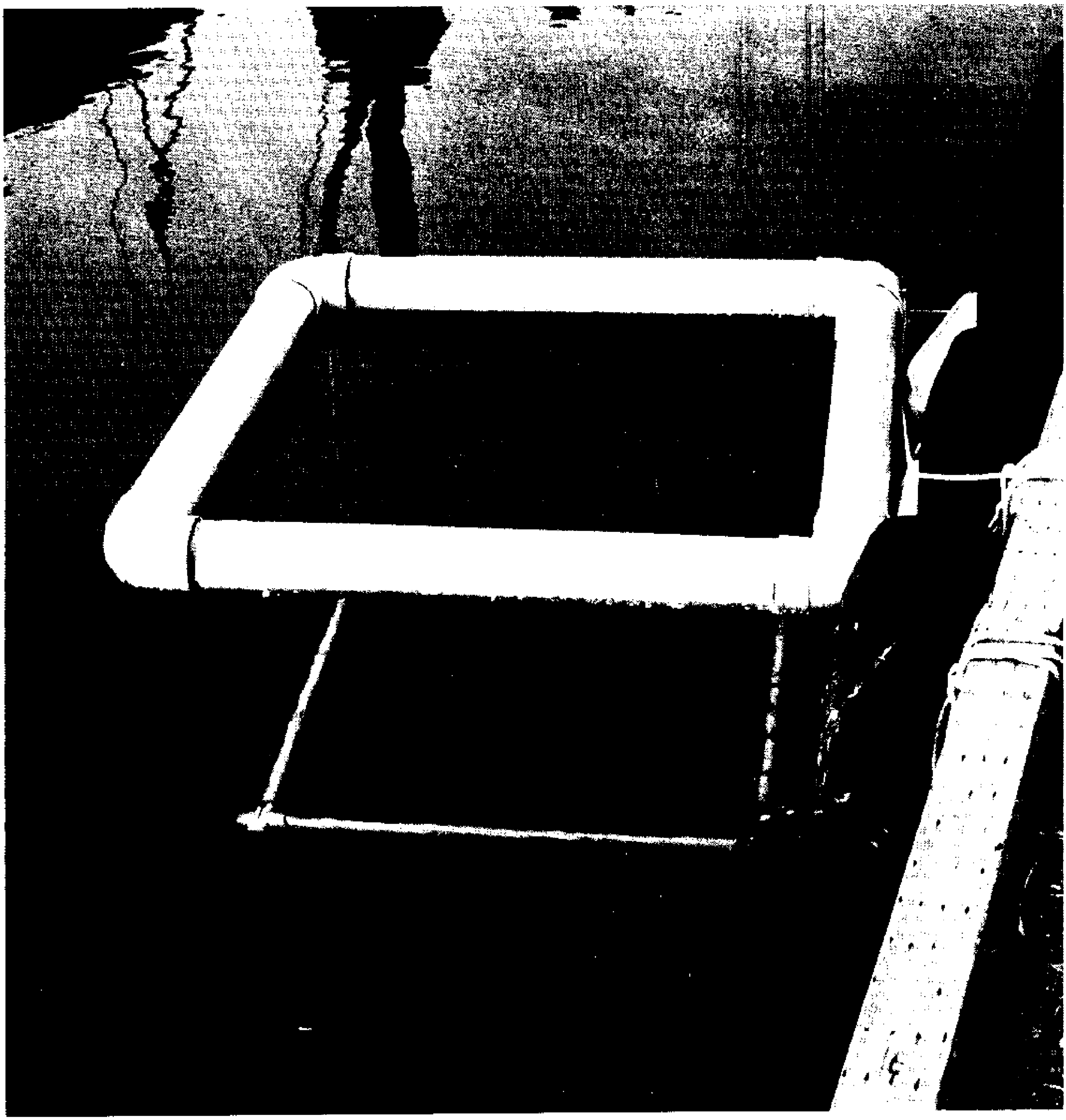

FIGURE 2.6 Square Plastic-Pipe Frame Module (0.75 x 0.75 m) Suspended from Plastic Pipe-Frame Float (The float is constructed of 4-in plastic pipe; the outside dimension of the float is 4 ft so that it will fit in a pickup truck. The square plastic pipe frame holds line or net containing the seaweeds. The line, net, or entire frame is readily removed from the float for weighing and measurement. Depth of the frame is easily regulated by adjusting the suspension lines and the entire assembly is easily handled by one person.)

FIGURE 2.7 Small Perforated Plastic Baskets Suspended from a Large Raft (Plastic mesh ["Vexar"] was heat welded to the basket as a liner. Clear plastic tops were added to prevent plants from sloshing out.)

FIGURE 2.8 Plastic Bag (4 x 8 x 4 ft deep) Suspended from Plastic Pipe Raft (Water motion and water pumping were provided by an airlift pump in the bottom center of the bag. Screened perforations (4 in diam.) allowed for water flow out of the bag as the airlift pump introduced new water. The aeration also kept the free-floating plants tumbling in the water within the bag. At sheltered sites, much less freeboard than is illustrated here was adequate to prevent plant loss.)

provided to maintain bag shape (Lindsay and Saunders 1979). Bag fabrics are quite susceptible to tearing and puncturing unless very sturdy (and expensive) bag materials are used. The light and flexible nature of these units is a useful feature; however, experiences showed that they offer no advantage over open modules (with line or net substrates). In special situations, such as to control water motion, nutrient additions, or herbivore exclusion or inclusion, they may prove useful.

Summary

The needs of a particular experiment will dictate to a great degree the type of small raft or culture module that can be used. The most useful of the units used in these experiments were the plastic pipe frame units and the linear units whether they were located at or near the bottom, in modest depths or near the surface. They are inexpensive to construct, the construction materials are readily available, they are compatible with many types of marine algae, they have a reasonable lifetime in the field, and they can be constructed in a range of sizes according to experimental needs. They also may be increased in a cellular or modular way to fairly large arrays.

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CALIFORNIA

AND CHINA

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3

MACROALGAL CULTURE IN CALIFORNIA AND CHINA

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Macroalgal Culture in California

Experimental macroalgal culture has been carried out for several years on the west coast of the United States. The genera that have been studied include *Macrocystis*, *Porphyra*, *Gracilaria*, and *Gelidium*. A nearshore test farm of *Macrocystis* has been installed and is now being harvested. This experimental farm consists of two plots, each 60 meters long and 40 meters wide, being planted with 361 plants that were originally collected from nearby kelp beds. One of the plots is fertilized, the other is not. Each plot has three different planting densities, that is, 1 plant per square meter, 1 plant per 2 square meters, and 1 plant per 4 square meters (Figures 3.1 and 3.2). The depth of the farm site is about 10 meters. The results of two harvests are shown in Tables 3.1 and 3.2. These results show that there is no significant difference between the fertilized and unfertilized plots, whereas differences between different planting densities are obvious. At higher planting density there is more per-unit-area production, but the proportion of dead plants is higher and the per-plant production is lower. The high density plantings form a surface canopy first, and the plants appear to elongate rapidly. Light conditions may play an important role in this phenomenon. Shading probably influences the high density plants. A better understanding of the growth and development of *Macrocystis*, and of how light influences the different parts of the plant at different stages, will be helpful in designing and planting future *Macrocystis* farms so as to obtain maximum survival and production.

In order to see how light influences *Macrocystis* growth and development, I initiated experiments that focus on the light demands of different parts of the *Macrocystis* plant. Trial experiments were begun in January using apical meristems as the experimental material. Four experiments have been completed to date; the results are shown in Table 3.3. Three kinds of measurements were made: the splitting rate, rate of length increase, and growth in wet weight. The results show that, like the meristem of *Laminaria*, the meristem of *Macrocystis* does not grow well in strong daylight. The best light level for meristematic splitting is about 10 percent or less of full surface daylight. The best light level for growth in length is higher--about 20 percent of full surface daylight. Optimal levels for growth in wet weight are the highest, about 30 percent of

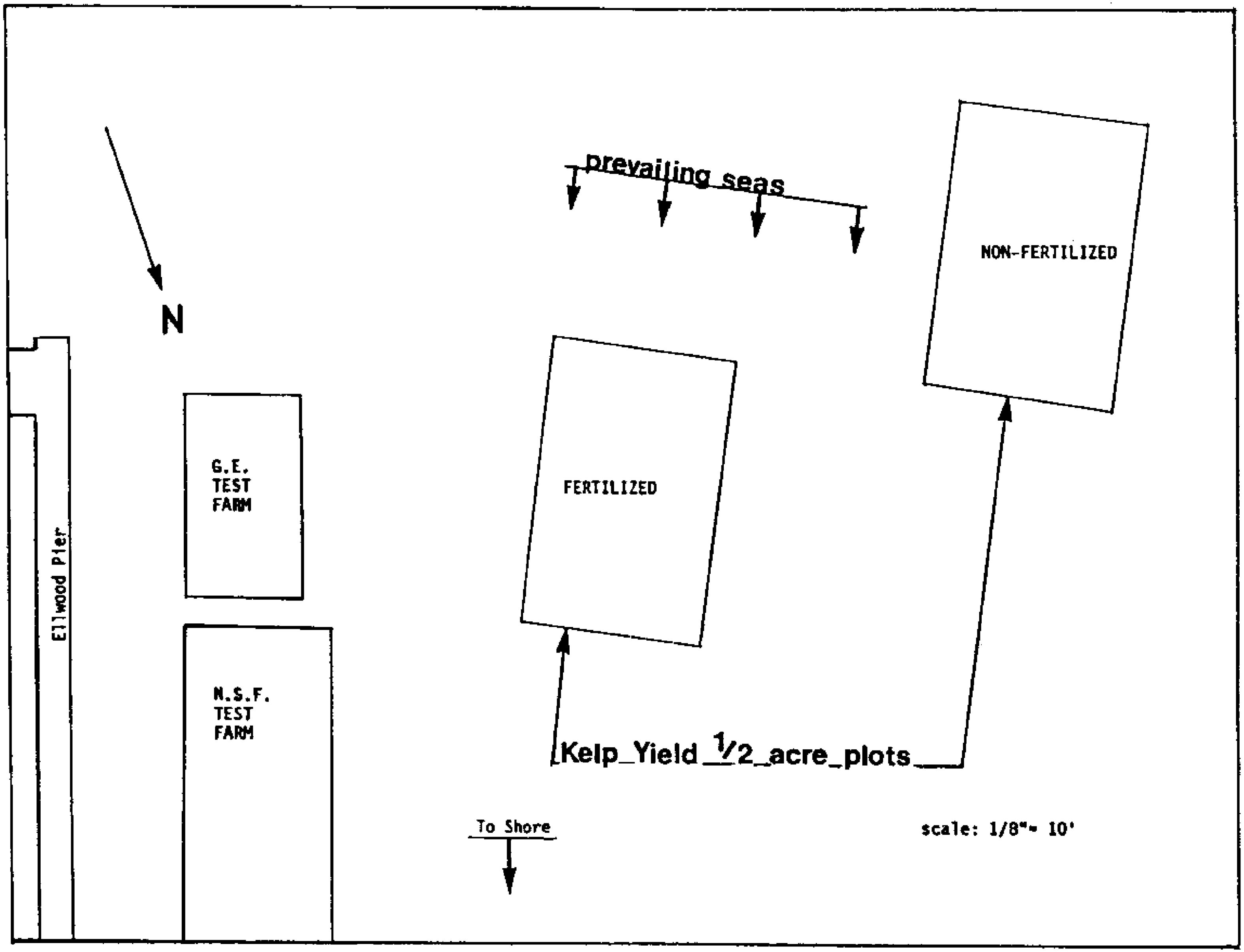


Figure 3.1 Orientation of Neushul Mariculture Inc. Kelp Yield Farm
(Source: Mike Stanfill (6/9/81)

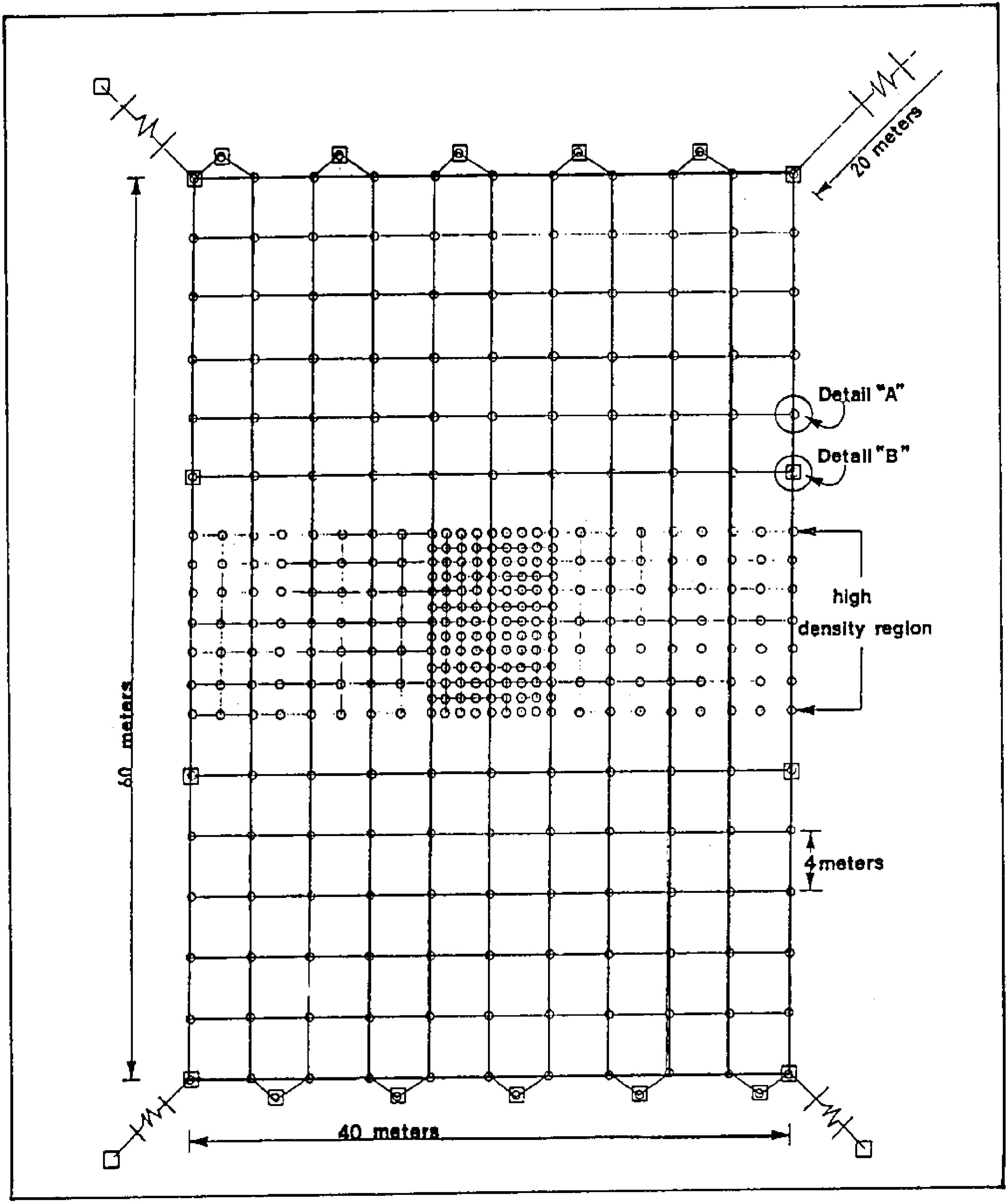


FIGURE 3.2 Detail of Kelp Yield Farm
Source: Mike Stanfill (6-9-81)

PLANTING DENSITY	# OF INDIVIDUALS
perimeter plants	10-25
4 meter	132
2 meter	112
1 meter	117

scale: 3/4"=4 Meter

TABLE 3.1 Results of First Harvest

Density		4 x 4 m 1 plant	2 x 2 m 1 plant	1 x 1 m 1 plant
Harvest/plant	UF	24.60 ± 18.04	18.31 ± 13.42	13.68 ± 12.80
Kg wet weight	F	22.04 ± 16.68	16.24 ± 14.38	13.06 ± 12.20
Frond/plant	UF	26.17 ± 9.50	25.31 ± 8.25	24.02 ± 8.60
	F	26.52 ± 11.06	25.63 ± 8.52	24.64 ± 8.57
Proportion of dead	UF	2.3%	6.3%	10.3%
%	F	3.0%	3.6%	13.0%
Production/ plant	UF	224.46 ± 157.02	170.16 ± 125.46	119.28 ± 112.50
Wet g/day	F	199.12 ± 146.49	139.21 ± 119.49	113.10 ± 103.15
Biomass yield	UF	14.03	42.54	119.28
Wet g/m^2/day	F	12.45	34.80	113.10
Projected yield*	UF	1.75	5.34	14.97
(Dry ash-free) t/acre/year	F	1.55	4.37	14.19

*Based on the assumption that growth is the same each quarter of the year.

TABLE 3.2 Results of Second Harvest

Density		4 x 4 m plant	2 x 2 m plant	1 x 1 m plant
Harvest/plant	UF	26.16 ± 29.69	15.84 ± 20.07	9.09 ± 12.16
Kg wet	F	28.95 ± 28.95	17.75 ± 20.11	10.20 ± 14.75
Frond/plant	UF	27.28 ± 23.31	21.22 ± 19.31	13.00 ± 12.81
	F	29.75 ± 21.58	21.61 ± 19.37	12.62 ± 13.59
Proportion of dead	UF	9.8%	10.0%	25.0%
%	F	13.0%	13.4%	27.4%
Production/ plant	UF	240.08 ± 266.69	138.56 ± 177.03	85.17 ± 112.54
Wet g/day	F	272.17 ± 243.21	170.55 ± 187.87	97.43 ± 136.36
Biomass yield	UF	15.01	34.64	85.17
Wet $g/m^2/day$	F	17.01	42.64	97.42
Biomass yield	UF	5.48	12.64	31.09
Wet $kg/m^2/year$	F	6.21	15.56	35.56
Projected yield*	UF	1.87	4.35	10.69
t/acre/year (Dry ash-free)	F	2.12	5.36	12.23

*Based on the assumption that growth is the same each quarter of the year.

TABLE 3.3 Light Demands of *Macrocystis* Meristem

Exp.		Highest light at noon	Increasing of splits	Length growth	Wet weight growth
		Ein/ m^2sec	number/days	mm/day	g/day
I.	(greenhouse)	1,181		6.05 ± 0.35	
	Jan. 19-	95		4.40 ± 0.28	
	Feb. 2	58		3.35 ± 0.64	
		34		3.35 ± 0.64	
		9		0.17 ± 0.00	
II.	(greenhouse)	1,330		3.60 ± 1.36	0.39 ± 0.20
	Feb. 21-	600		3.60 ± 2.25	0.29 ± 0.11
	Mar. 3	52		1.72 ± 0.46	0.18 ± 0.07
		15		1.40 ± 0.48	0.05 ± 0.01
		1.3		0.36 ± 0.35	0.03 ± 0.03
III.	(yard)	1,990	5.8 ± 3.27	5.38 ± 1.92	0.46 ± 0.21
	Apr. 8-	680	11.2 ± 4.92	7.40 ± 3.75	0.79 ± 0.62
	Apr. 18	242	14.0 ± 3.39	8.24 ± 3.45	0.45 ± 0.15
		180	13.0 ± 5.47	5.74 ± 1.92	0.20 ± 0.06
		0.5	0	-0.48 ± 4.00	-0.05 ± 0.02
IV.	(yard)	2,050	3.3 ± 2.3	3.50 ± 0.45	0.10 ± 0.07
	Apr. 22-	728	6.7 ± 1.5	7.25 ± 1.95	0.36 ± 0.08
	Apr. 30	169	12.6 ± 5.5	5.21 ± 2.69	0.22 ± 0.04
		57	4.3 ± 3.1	3.05 ± 1.26	0.06 ± 0.01
		11	2.7 ± 1.2	1.58 ± 0.58	0.02 ± 0.02

full surface light. The protection of the sensitive meristem from strong light may be important in getting higher yields, since lower light allows the meristem to produce more new blades by splitting. More work is needed to test this hypothesis.

Macroalgal Culture in China

There has been rapid development of macroalgal cultivation in China since 1949. Before then there was no actual macroalgal cultivation; all algal products were obtained from harvests of natural populations. The annual production of *Laminaria* was less than 60 tons dry weight, and production of *Porphyra* was less than 200 dry tons. China had to import 15,000 tons of dry *Laminaria* from Japan to meet the traditional and medical needs of the Chinese people. People living in inland areas usually eat *Laminaria* to cure or take precautions against goiter. Now, China produces 275,000 dry tons of *Laminaria* and 7,500 dry tons of *Porphyra* each year (Table 3.4), with 99 percent of this produced by raft cultivation.

Both *Laminaria* and *Porphyra* cultivation in China have gone through three development stages: enhancement, semiartificial cultivation, and artificial cultivation. Enhancement involves the manipulation of natural algal populations, and implies that modifiedd natural algal beds can produce more than would unmodified beds. Enhancement methods include the spreading of desirable species in the natural beds so as to increase the probability of their spores becoming established. Enhancement can also involve eradicating weed algae and animals, and following a specified harvest time and frequency so as to protect the crop.

Cultivation is a very recent activity, although it developed thousands of years ago with land crop plants. In-the-sea cultivation involves the provision of artificial substrates; this is the demarcation between enhancement and cultivation. Semiartificial cultivation involves control over the primary stages of plant development even though seedstocks of the cultivated alga are still not under full control by man. Artificial cultivation is an advanced stage of macroalgal cultivation; it entails that not only the cultivation processes but also the seedstocks are under full control. Enhancement is often better than exploiting natural populations, semiartificial culture is better than enhancement, and artificial culture is the most productive. The history of macroalgal cultivation proves that the more control over the cultivation process, the greater and more reliable is production and the higher the quality. The process of development leading from enhancement to artificial cultivation may serve as a model for all macroalgal cultivation, and the recognition of this historical process may help to orient research that will speed it up.

At present, all *Laminaria* cultivation in China is on artificial substrates. Seedstock plants are grown from zoospores to lengths of 1 to 3 centimeters in tanks inside greenhouses on

TABLE 3.4 Annual Production of Cultivated Macroalgae in China

	Laminaria	*Porphyra*
Annual production		
dry t	275,000	7,500
wet t	1,512,500	112,500
Production area		
hectare	27,500	3,400
acre	67,953	8,401
Yield/hectare (mean)		
dry t	10	2
wet t	55	30
Yield/acre (mean)		
dry t	4.05	0.89
wet t	22.26	13.39

Laminaria wet/dry 5.5 = 1
Porphyra wet/dry 15 = 1

Production period 6 months

land, under low temperature conditions (Figure 3.3). This kind of culture system in China produces millions of young *Laminaria* in a very effective and economical way (see below). Adult plants are cultivated on ropes in the sea (Figures 3.4 and 3.5).

At present all *Porphyra* cultivation in China is also on artificial substrates. During the conchocelis phase of *Porphyra*, it is cultivated using shells of *Meretrix* as the substrate. The shells are kept in tanks inside greenhouses at normal temperature conditions (Figure 3.6). The techniques for conchocelis cultivation in China are so successful that conchospore collecting can be done completely artificially inside the culture tanks without having to move shells to the sea to induce sporulation during the spore-collecting season. The cultivation of the *Porphyra* leafy phase is also done by raft culture. Most of the rafts are installed in the intertidal zone, using a unique semifloating Chinese system (Figures 3.7 and 3.8). The per-unit area production of Chinese *Porphyra* cultivation is high. For example, China produces about one-third the amount of the total Japanese production, but the Chinese production area is much smaller--only about one-ninth of the Japanese production area.

Raft Culture Techniques for *Laminaria*.

Biological Aspects of Cultivated *Laminaria japonica* under Raft Culture

Although the sporophyte of *L. japonica* is usually biennial in its native habitat, under raft conditions it becomes annual. The sporophyte matures in only 5 to 7 months instead of 2 years. The cultivated *Laminaria* sporophyte goes through six stages from a 3 to 5 centimeter long young plant to a 3 to 7 meter long adult plant, when it begins to decay (Figure 3.9). *L. japonica* is a single-blade plant with a growing point (meristem) at the bottom part of the blade. This part does not grow well when exposed to strong light. The most favorable environmental conditions for *L. japonica* growth are as follows:

Temperature: Water temperatures of 1 to 13°C are good, while 5 to 10°C is best for growth in length; 13 to 20°C is the optimal temperature for dry-weight increase.

Light: Light levels of one-half to one-fourth full-surface-daylight are optimal for growth in length, while optimal dry-weight increase is achieved at higher light levels. The meristem cannot withstand strong daylight especially when the plants are young, and will produce a twisted and stunted plant under such conditions.

Nutrients: The optimal nitrogen (NO_3-N and NH_4-N) concentration is 7 μm/l for normal growth, while 14 μm/l is very good and at levels of less than 3.5 μm/l artificial fertilization is necessary.

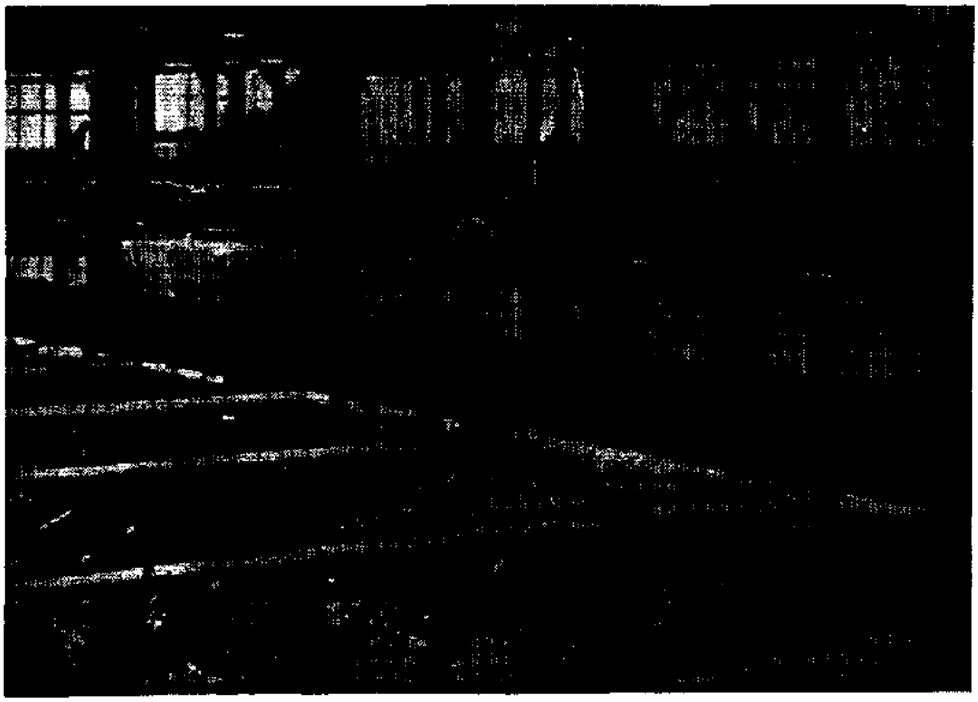


Figure 3.3 Chinese Nursery Cultivation of *L. japonica*

Figure 3.4 Near-shore Cultivation of *L. japonica* on Ropes in China

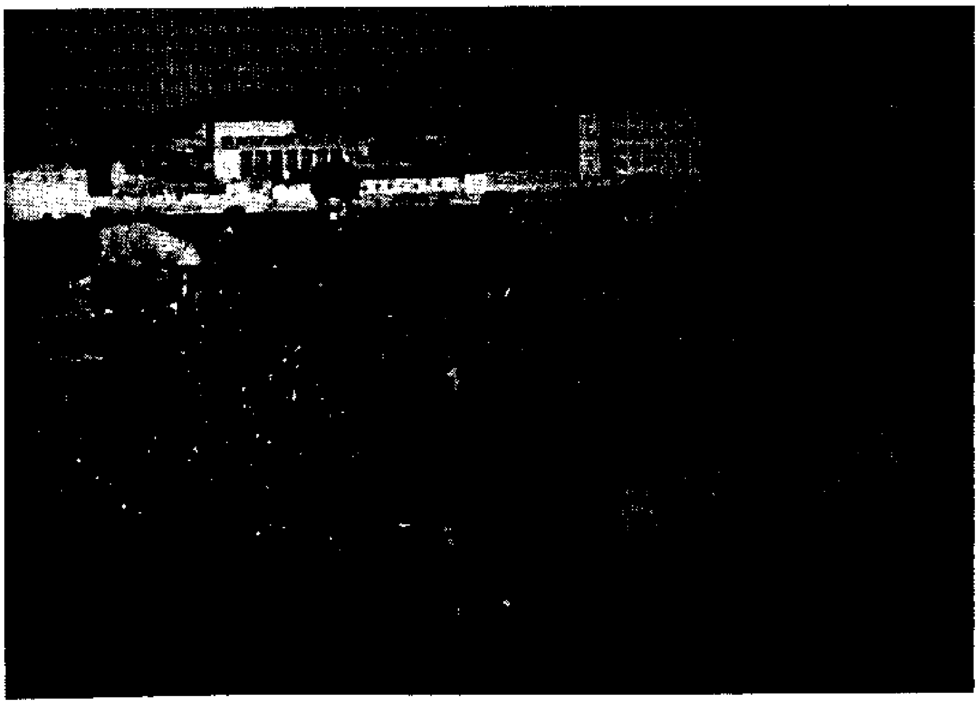


Figure 3.5 Harvesting *L. japonica* in China

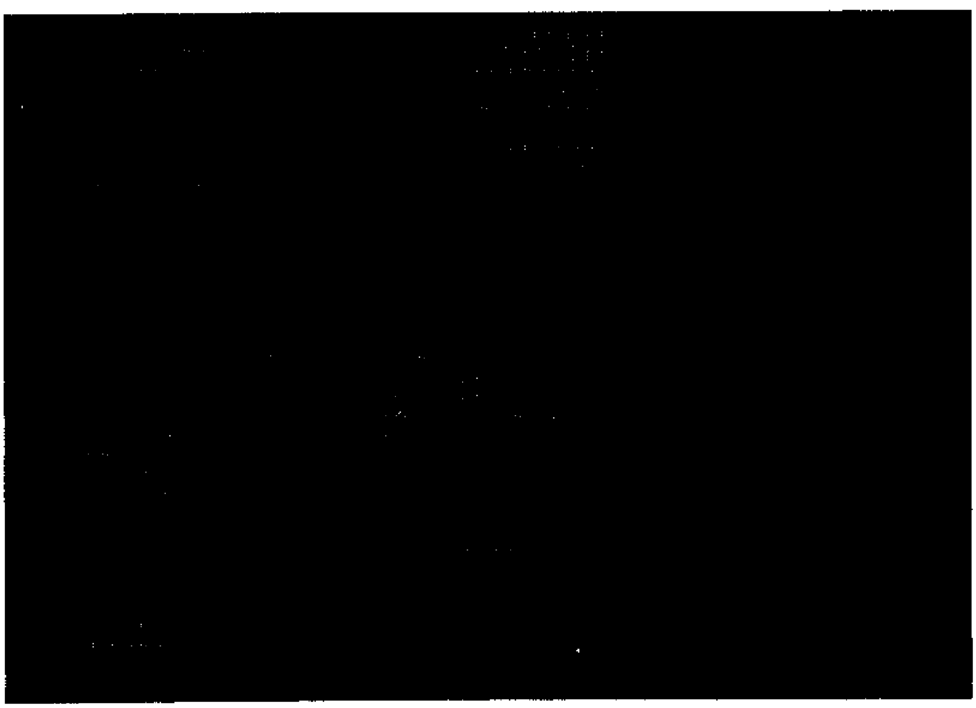


Figure 3.6 Nursery Cultivation of *Porphyra* using *Meretrix* Shells

Figure 3.7 Porphyra Nets in the Intertidal Zone

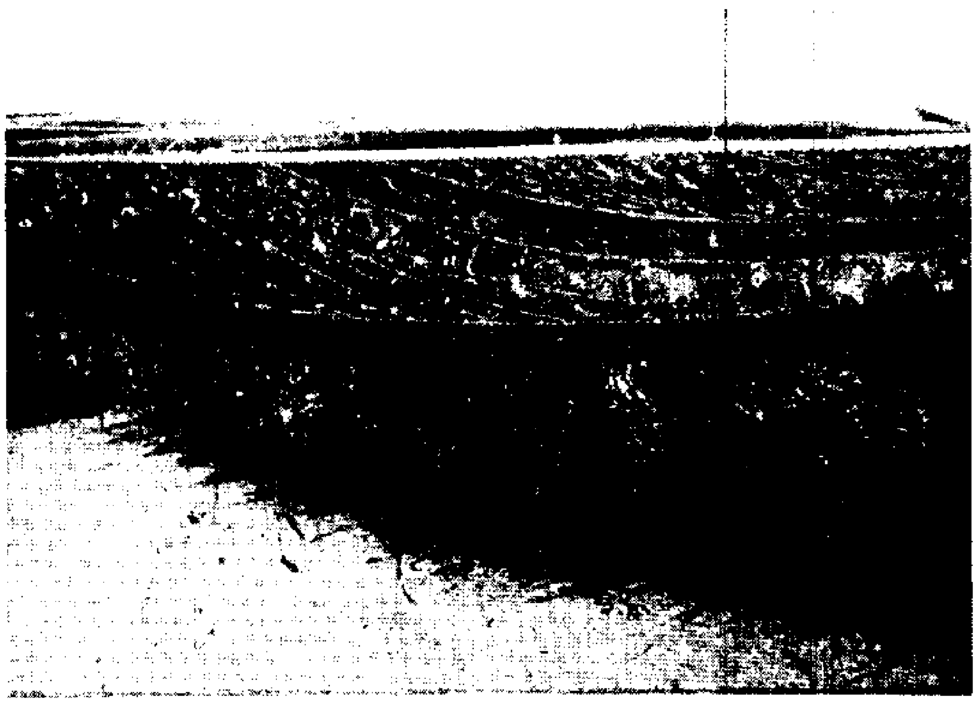


Figure 3.8 Porphyra Crop Ready for Harvesting

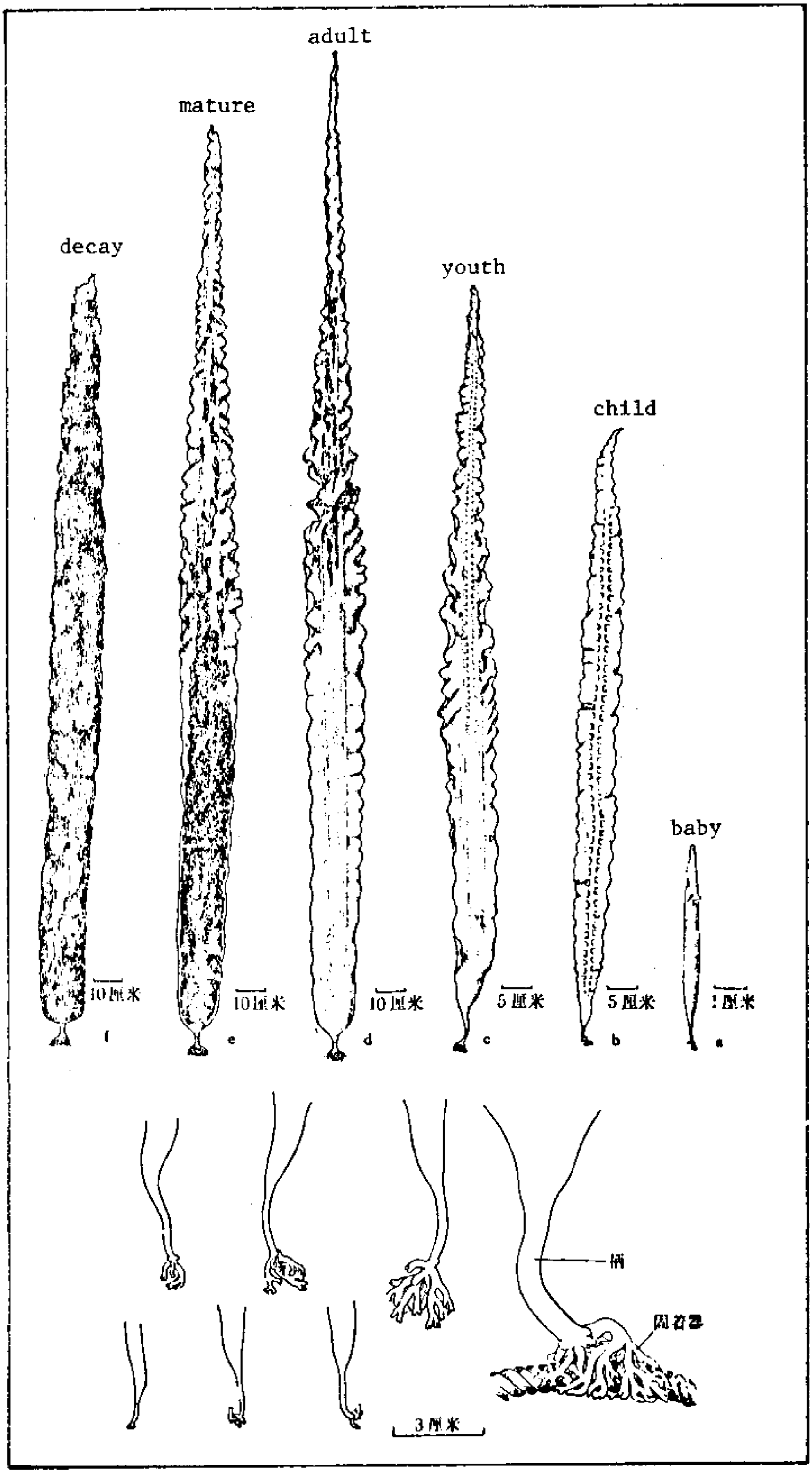


Figure 3.9 L. japonica Life Stages

Current: A current flow of 20 cm/sec or more is good. The stronger the current the better, but more than 80 cm/sec (about 1.5 knots) makes it difficult to install and keep the cultivation rafts in place.

The Cultivation Raft

Many kinds of *Laminaria* cultivation rafts are used in China. The single-line raft is the most usual and was the original design; its construction is shown in Figures 3.10 and 3.11. The plants grow attached to the ropes (Figure 3.12).

The functions of a *Laminaria* cultivation raft are: (1) to provide a supporting system for the *Laminaria* population cultivated in the sea which is strong enough to withstand storm waves and currents; (2)to provide an adjustable culture system that can be manipulated so as to produce the best conditions for *Laminaria* cultivation; (3) to be easy to check and repair in case of tangling or damage, and to facilitate routine checking and observation; and (4) to be simple and economical without requiring expensive materials.

The major considerations when installing a *Laminaria* cultivation raft are:

1. *Depth of the cultivation site*: The depth can range from 3 to 30 meters at low tide, but depth of 5 to 15 meters is best. Plants grow well if rafts are installed more than 30 meters deep, but since rafts need stronger anchor lines and more construction materials, making them expensive, we usually do not install them at such depths.

2. *Bottom condition*: The best type of bottom for raft installation is half sand and half mud. This type is good for the installation of stakes at the bottom, which is the most popular method for mooring the raft and is very effective, fast, and inexpensive for large-scale cultivation. The stakes are made of wood, 1 to 1.5 meters high and 0.15 meter in diameter. Mooring ropes are tied to the stakes, which can be used for many years after being stuck into the bottom. Rocky bottom is also good for cultivation. In such regions anchor blocks made of large rocks or concrete with a weight of 1 ton are used.

3. *Natural light and temperature conditions*: Is it necessary to find a place for culture raft installation where the natural conditions are similar to *Laminaria*'s native habitat? It may not be. *Laminaria japonica* is being successfully cultivated at various places in China with very different environmental conditions. Annual water temperatures (mean) range from 11 to 21^{o}C; transparency levels can range from 0.1 meter secchi disc to 15 meters secchi disc. These conditions are very different from those found in its native habitat of northern Japan in the Hokkaidao region, where water temperatures are low (10^{o}C) and the water is very clear.

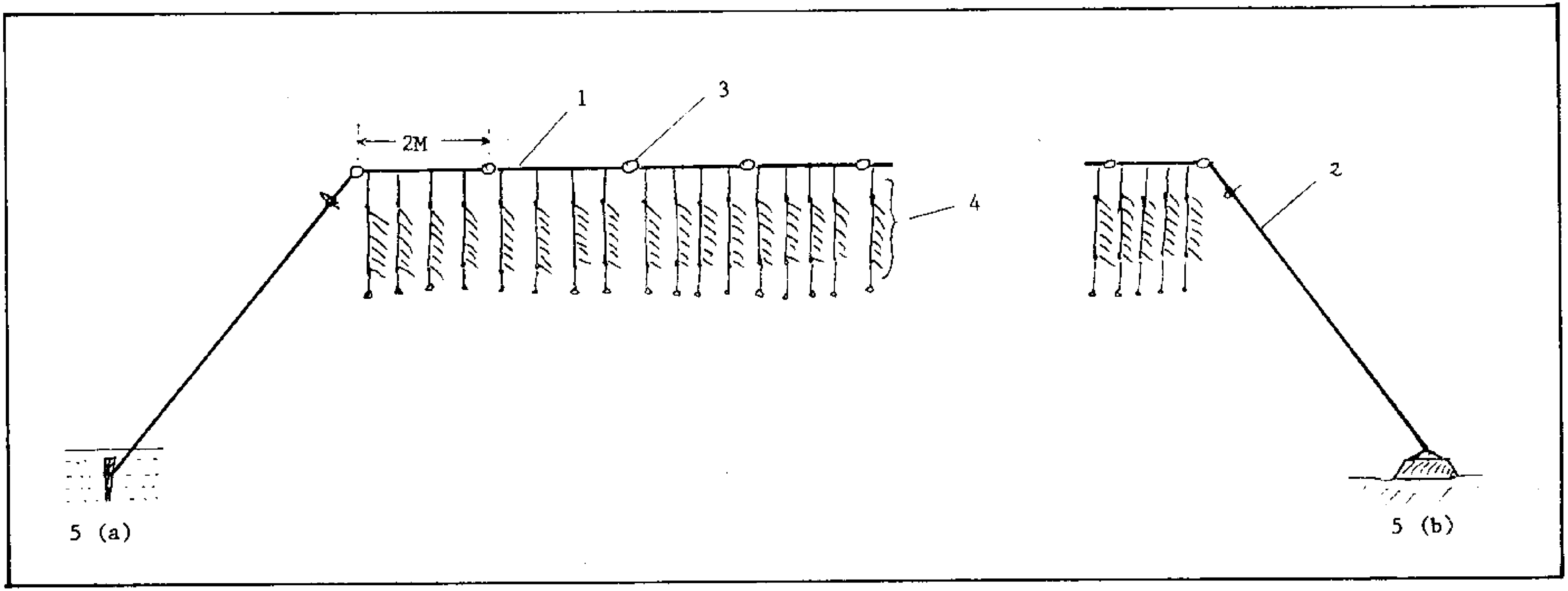


Figure 3.10 Single Line of *L. japonica* Rope Farm

1. Floating rope (60 m)
2. Mooring rope
3. Buoy (glass bulb, diam.= 76 cm)
4. Culture rope: Hanging rope, Plant rope, Weight stone
5. Anchor: (a) Pile, (b) Concrete block

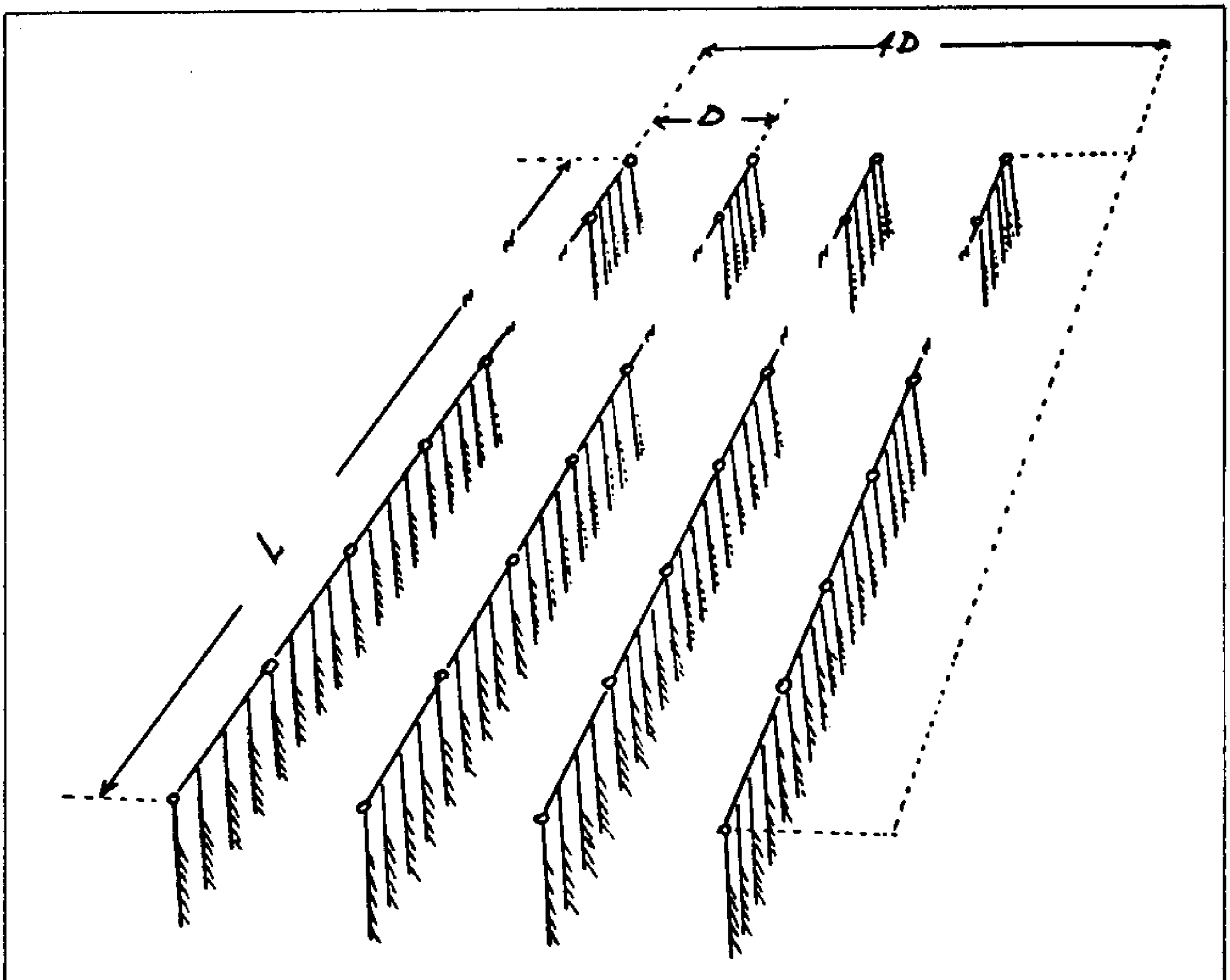


Figure 3.11 Chinese L. japonica Rope Farm

Figure 3.12 Holdfasts of *L. japonica* Intertwined on Culture Rope

4. Natural nutrient levels: Nitrogen sometimes becomes a limiting factor in certain places at certain times. Fertilizers should be applied only when necessary. It is best to find cultivation sites where nutrient levels are high.

5. Wave, wind, and current climates: For test farms, pilot cultivation, or small-scale cultivation in general it is better to choose a safe, protected bay. However, for large-scale cultivation, for example, 500 to 1,000 hectares, it is better to farm in open water where stronger waves, wind, and currents can provide better conditions for the very large-scale cultivated kelp populations.

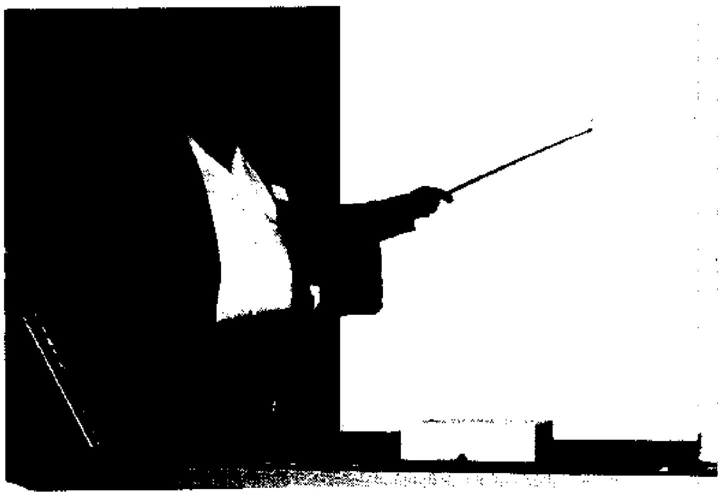
6. Orientation of the raft: This is important to ensure both that the rafts stay in place and that the plants grow well. Single-line rafts are placed perpendicular to the prevailing current. When many are so placed, they respond favorably to the current, improving light penetration and reducing entanglement.

7. Tension of raft anchors: The tension on the raft should be moderate, and lines that are either too loose or too tight are undesirable. Generally, it is best to let the first surface buoy on the line half float and half sink at high tide. Under these conditions, the anchor-line tension is optimal.

8. Length of raft mooring lines: The mooring rope should be about two to three times longer than the water depth at high tide.

Generally speaking, all measures, techniques, construction, and materials applied in raft cultivation should first consider the biological aspects of the plant. New research results often provide new insights into how methods or techniques can be improved. The more we understand our cultivated algae, the more effective control we have and the better the cultivation results we can achieve. In China we have found that a comprehensive and continuous research program on the cultivated plants dealing with taxonomy, morphology, physiology, ecology, genetics, and physioecology, or, as we say, experimental phycoecology, provides a sound basis for cultivation programs.

FLORIDA



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4

LAND-BASED CULTIVATION OF SEAWEEDS: AN ASSESSMENT OF THEIR POTENTIAL YIELDS FOR "ENERGY FARMING"

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In Florida, there has been considerable effort since 1976 by John Ryther and his colleagues, primarily at the Harbor Branch Foundation, near Fort Pierce, to assess the potential of seaweeds as a source of biomass for conversion into methane. This effort was funded, in sequence, by the Energy Research and Development Authority, the Solar Energy Research Institute. Presently, the project is being reorganized as part of the Gas Research Institute/Institute of Food and Agricultural Sciences "Methane from Biomass and Waste Program." This latter program is looking at the potential of a number of different types of biomass (e.g., trees, agricultural crops and wastes, freshwater plants, seaweeds), with the goal of developing a comprehensive alternative energy program, based on renewable biomass, for the state of Florida.

This chapter is a summary of the experimental seaweed cultivation that has taken place in Florida as part of this work. In particular, the development of one species (*Gracilaria tikvahiae*) as a potential energy crop will be traced through several levels of experimentation.

Production of Biomass

The most important criterion that determines the potential of a species to serve as an "energy crop" is a rapid and sustained production of biomass (i.e., yield). Additional considerations are ease of cultivation, complexity of life cycle, and the simultaneous production of other economically important materials (e.g., phycocolloids). For any given geographical area, the best species, in regard to yield, will be determined by the local climate (i.e., light and temperature conditions). Thus it is important that the native flora of the area be "screened" for the presence of fast-growing species that are most suitable to local environmental conditions. It is highly unlikely that fast-growing exotic species will ever be introduced into new areas for large-scale *in situ* cultivation because of concerns over their impact on the local ecosystem, as demonstrated by man's unintentional introduction of exotic seaweed, such as *Sargassum muticum* and *Codium fragile*.

Accordingly, the first step in the research program at the

Harbor Branch Foundation was to measure the potential yields of local seaweeds in small outdoor tanks called "screening troughs" (Figure 4.1) (see list at end of chapter). Of over 55 species that were examined in these troughs, the best performer, on the basis of sustained yields, was the red seaweed *Gracilaria tikvahiae* (Figure 4.2), which had an annual average of 35 g dry weight $\cdot m^{-2} \cdot day^{-1}$, which is equivalent to an annual yield of 128 dry metric tons $\cdot ha^{-1} \cdot yr^{-1}$. Other species, particularly green seaweeds such as *Enteromorpha*, *Chaetomorpha*, and *Ulva*, could grow faster than *Gracilaria* for short periods, but high yields were not sustained for very long. The yield of *Gracilaria* in these screening troughs is among the highest for any plants in the world under any conditions. Of course, these data represent what is possible under rather idealistic conditions; they demonstrate the potential of *Gracilaria* to produce biomass, but they are probably not attainable on a commercial level, at least in the near future. It is important to note that the method of cultivation employed on this small scale was very energy-intensive, i.e. large amounts of flowing seawater and aeration were required, and could not be practically employed for the commercial cultivation of *Gracilaria* for the purpose of bioconversion because of an unfavorable net energy balance.

Gracilaria has been grown in larger tanks than these screening troughs. In one configuration (Figure 4.3), *Gracilaria* has been successfully grown for several years, with an average productivity of 22 to 25 g dry weight $\cdot m^{-2} \cdot day^{-1}$ (80 to 91 dry metric tons $\cdot ha^{-1} \cdot yr^{-1}$). Most of the research has involved one particular clone ("ORCA") of *G. tikvahiae* that was first isolated in December 1977. From an initial weight of a few grams, many tons of this clone have been grown at the Harbor Branch facility. During this time, the clone has not reproduced sexually; rather it propagates itself vegetatively, reproducing only through fragmentation. The use of such a sterile clone is useful because, once a desirable clone is selected, it can be maintained, without changes in its genetic makeup, for long periods.

This energy-intensive tank culture has been successfully scaled up to tanks having a surface area of 29 square meters and a volume of 24,000 liters without any decrease in the above yield. Additional research has indicated that aeration and seawater flow can be reduced without significant losses in yield, but probably not to a point where this method would be economically viable for the production of methane. However, it is possible that this type of culture could be successfully employed if *Gracilaria* were to be cultivated for the production of agar, an expensive phycocolloid that has many commercial applications, primarily in the food and drug industries.

While additional research continues on minimizing energy inputs into this type of tank culture, there have also been some attempts to grow *Gracilaria* in what may be considered a non-intensive type of culture, PVC-lined earthen ponds (Figure 4.4). These ponds varied in size from 10 to 20 m^2, in depth from 0.4 to 0.8 square meter, and had volumes up to 25,000 liters. In most

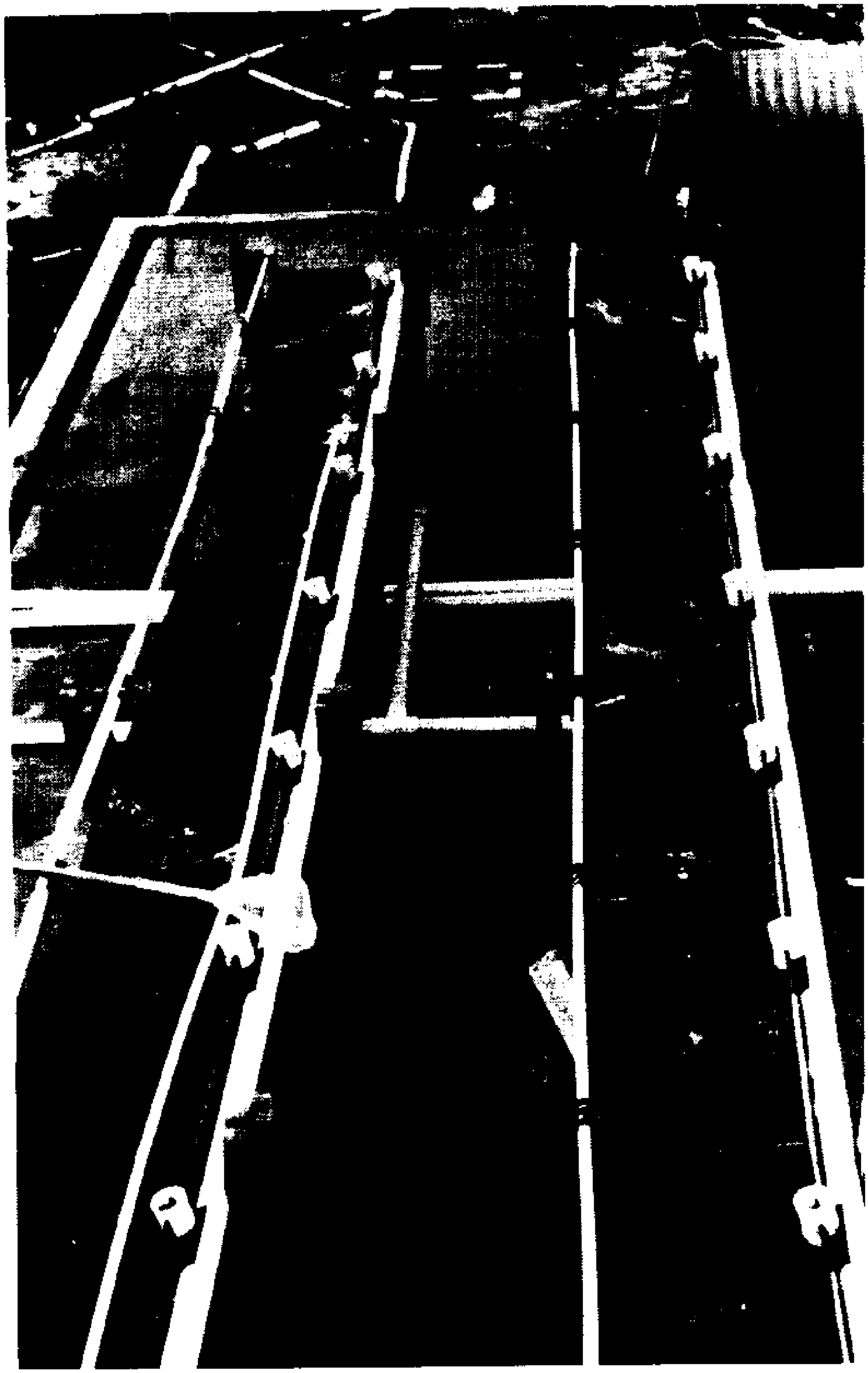

FIGURE 4.1 "Screening troughs" used in the screening of seaweeds at the Harbor Branch Foundation (These tanks were constructed from PVC pipe and sectioned into small [55 liters] chambers. Seaweeds were heavily aerated and received over 20 culture-volume exchanges per day of enriched seawater.)

FIGURE 4.2 *Gracilaria tikvahiae* (the most successful species during screening trials conducted in 1976-1977 in tanks like those in Figure 8.1)

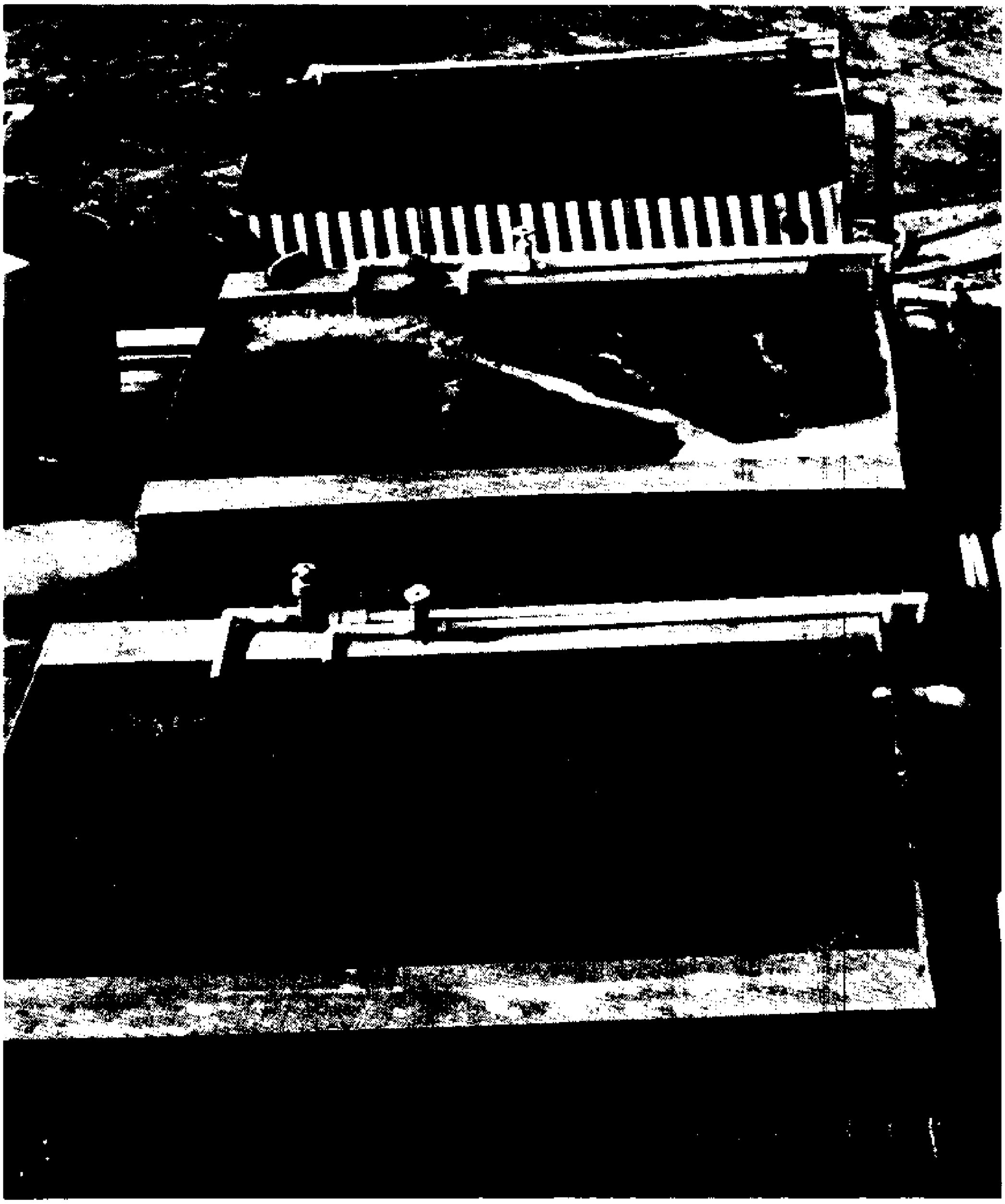

FIGURE 4.3 Tanks for *Gracilaria* cultivation, constructed from aluminum culvert pipe (Typical flow rates were 4 volume exchanges/day [volume was 2,600 liters]. Heavy aeration was used to keep the plants in continuous suspension. Similarly constructed tanks have been used with volumes up to 24,000 liters.)

FIGURE 4.4 PVC-lined earthen ponds, used to provide a less intensive mode of cultivation (Bottom area ranged from 10 to 20 m2, depths were 0.4 to 0.8 m, and volumes were 5,000 to 25,000 liters. Typically no aeration was employed and flow rates were 2 volume exchanges/day.)

cases, *Gracilaria* was scattered, unattached, along the bottom of the ponds. Initially, no aeration was employed, and the exchange of seawater was relatively low (2 volume turnovers/day). Yields in this type of "bottom culture" were significantly lower than in the energy-intensive method and usually ranged from 5 to 8 g dry weight $\cdot m^{-2} \cdot day^{-1}$ (18 to 29 dry metric tons $\cdot ha^{-1} \cdot yr^{-1}$). Besides this considerable reduction in yield compared to the more intensive cultivation, other problems were encountered that were primarily associated with a reduction in water motion. The most serious of these was the growth of diatom mats on the sides of the ponds. These mats eventually detached from the liners, became entrapped in the seaweed, and floated *Gracilaria* to the surface, where, without agitation, surface temperatures reached 40°C in the summer. Such a high temperature is lethal to *Gracilaria*. In addition, once *Gracilaria* was floating, it was quite susceptible to being blown to one end of the pond by even moderate winds. The resulting heterogeneous distribution of seaweed further reduced yields--during the day, part of the pond was overcrowded with seaweed, causing much self-shading, while the rest of the pond was empty; thus, light energy, the ultimate limiting factor for seaweed growth, was squandered in the system. Also, at night, the dense patches of seaweeds became quite anaerobic. These problems could be alleviated by applying low levels of aeration to the ponds, specifically, enough aeration to circulate water around the seaweed without moving the plants themselves. In so doing, thermal stratification was eliminated, diatoms and other potential fouling organisms were more readily washed out of the pond, the distribution of *Gracilaria* within the pond was fairly homogeneous, and anaerobic conditions were avoided. Consequently, yields of *Gracilaria* in such ponds were approximately twice that of completely unaerated ponds. While this is a considerable improvement, these yields were still only about half of the energy-intensive mode of cultivation. While actual net energy balances have not yet been determined, this type of cultivation ("bottom culture" with minimum aeration) may be a good compromise between the two extremes, especially if aeration need not be applied continuously (e.g., only summer days).

The beneficial effects of aeration for seaweeds can be attributed to the following: (1) it increases photosynthetic efficiency, by rotating the seaweeds in such a way that they are able to maximize the absorbance of light rather than having a high amount of self-shading; (2) it increases nutrient uptake rates, by reducing diffusion boundary layers; (3) it increases the availability of metabolic gases (carbon dioxide, oxygen), both by reducing diffusion boundary layers and direct enhancement from the airline; and (4) it flushes out competing algal cells and spores, thereby reducing the epiphyte problem. While the effects of aeration are clearly beneficial to seaweeds being cultivated in land-based systems, it appears that its requirement is partly an artifact of the culture configuration; seaweeds *in situ* derive the same benefits as above from water movement (i.e., currents).

"Bottom culture" was also studied, on what may be considered a pilot scale, in a 0.1-hectare (0.25-acre) pond (Figure 4.5). This pond was twice stocked with several tons of *Gracilaria*. Each time cultures were sustained for only 6 months, during the cooler months of the year. Mean productivity was ca. 7 g dry weight $\cdot m^{-2} \cdot day^{-1}$. In both years, growth stopped with the advent of warm summer temperatures. No aeration was employed in this pond. Serious problems were also encountered with grazing by amphipods. At present, no further work with this pond is planned. Research is concentrated on minimizing the amount of aeration and seawater flow required to grow *Gracilaria* and is being conducted in tanks.

Prospects

Clearly, there is a considerable amount of data that indicates that at least one seaweed, *Gracilaria tikvahiae*, has the potential to be an energy crop in a mariculture system. In addition, there are several other species under study in Florida that show promise. All of these seaweeds are readily digestible, with favorable methane production characteristics. Furthermore, with the utilization of digester residues as a replacement for conventional fertilizer and proper nutrient management, the problem of providing a relatively inexpensive fertilizer to a seaweed farm appears solvable.

The major limitation of this research is that it is land based; almost certainly, such a system will not have large-scale application for the purpose of bioconversion. Although it is possible that some small-scale applications are feasible if they are tied to other products/services (e.g., sewage treatment, polyculture systems, phycocolloid production), any significant energy farm will be located in open water. Thus, in order to test this whole concept, experimental seaweed farms will have to be deployed *in situ*.

While such a deployment is not immediately planned for the Florida project, it remains a long-term goal. The design of such a farm needs to be planned with considerable input from both biologists and engineers. It is important that the biology of the species involved is understood as fully as possible, especially in areas of environmental regulation of growth and reproduction, selection of fast-growing strains, and defining nutrient and harvesting strategies. Studies of possible locations for seaweed farms need to be made, with an emphasis on selecting a site that is most conducive to seaweed growth yet has minimal impact on the local environment and on other users of this resource. Given the biological and site constraints, engineers need to design appropriate structures that will survive the harshness of the ocean environment and yet be harmonious with the plants under cultivation. A well-engineered structure has no value if it does not provide a favorable environment for seaweed growth. Forums between biologists and engineers such as this workshop in New York are needed to form the symbiosis of biology and technology that will be required for the successful development of commercial seaweed farms.

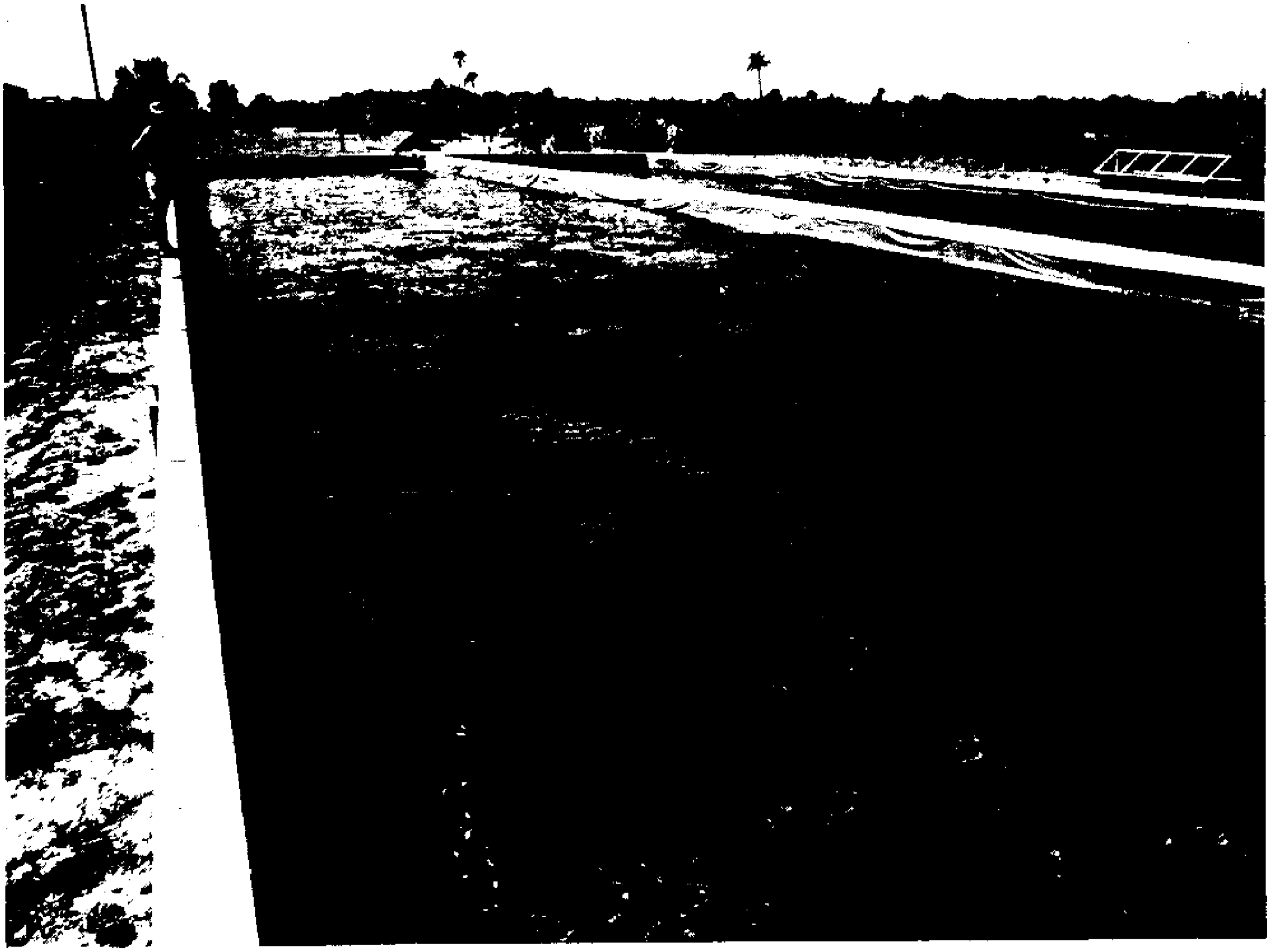

FIGURE 4.5 A 0.1-hectare (0.25-acre) pond used as a demonstration for nonintensive cultivation of *Gracilaria* (This PVC-lined pond had walls made of concrete blocks and a sand bottom.)

Whether or not energy farming will be viable in the foreseeable future is unknown. A rational decision can only be made after considerable experimentation and the development of a pilot-scale seaweed farm *in situ*. The uncertainty of fossil fuel reserves, including their costs and continued availability, prevent any meaningful economic projection at this time. At present, it appears that there is enough potential in seaweeds to serve as an alternative source of energy to merit further study. If successful, marine energy farms will help fulfill one of man's oldest dreams: to farm and harvest the sea.

Acknowledgements

Support for this research was provided by contracts from the Department of Energy (EY-76-S-02-2948) and the Solar Energy Research Institute (XR-9-8133-1), as well as the Harbor Branch Foundation. A number of individuals have participated in these efforts, including Dave Andrews, Kimon Bird, Tom DeBusk, Blake Faulkner, Cliff Habig, Brian Lapointe, Richard Stenberg, and Coddy Williams. Their contributions to the project, past and present, are gratefully acknowledged.

SOUTH CAROLINA

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5

A DESIGN FOR ENERGY-INDEPENDENT SEAWEED RAFT CULTURE IN TIDAL CREEKS AND RIVERS

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Introduction

The coasts of the Carolinas have great potential for seaweed mariculture. The area is relatively free from pollution and has an extensive system of marshes and tidal creeks. In the early 1940s, the coast was noted for its production of colloids from seaweeds to replace those previously furnished by Japan (Humm 1942, 1944). Sublittoral areas also contain good standing crops of seaweeds (Schneider and Searles 1978), many of which have potential for biomass or phycocolloid production. The harvesting of natural populations of these seaweeds should be avoided, however, because of their important role in supplying substrate, food, and other organic components of the marine environment.

Tidal creeks and rivers, where waters are wholely influenced by ebb and flood tides, offer many advantages for aquaculture. They offer nutrient-rich waters where salinity fluctuations are minimal (20-28 ppt) owing to low freshwater drainage. A lack of wave energy allows luxurious algal growth and eliminates shearing of plants on raft culture facilities. A lower diversity of fauna is reflected in the paucity of grazers as compared to estuaries. Many tidal creeks are wide and deep enough to accommodate large raft facilities and are often unused for commercial navigation. In microtidal areas, the depth fluctuations are minimal, with channel depths often exceeding 6 meters at mean low tide.

Description

The proposed raft facility is the result of the testing of scale model and small-scale prototypes and years of field and culture studies of seaweeds. This chapter will present the design of the raft and its adaptations to tidal creek or river habitats.

Figure 5.1 illustrates the "I" beam construction, which is the central structure of the facility. The raft is 30 feet (9.4 m) long and 20 feet (6.3 m) wide. The wooden plank surface is floated by styrofoam blocks at each end of the "I." The buoyancy and flexibility of the structure is similar to that of a floating pier. In detail, the wooden planks are bolted to a galvanized angle-iron frame, and the styrofoam blocks are lashed to this frame by replaceable steel bands. A keel adds stability

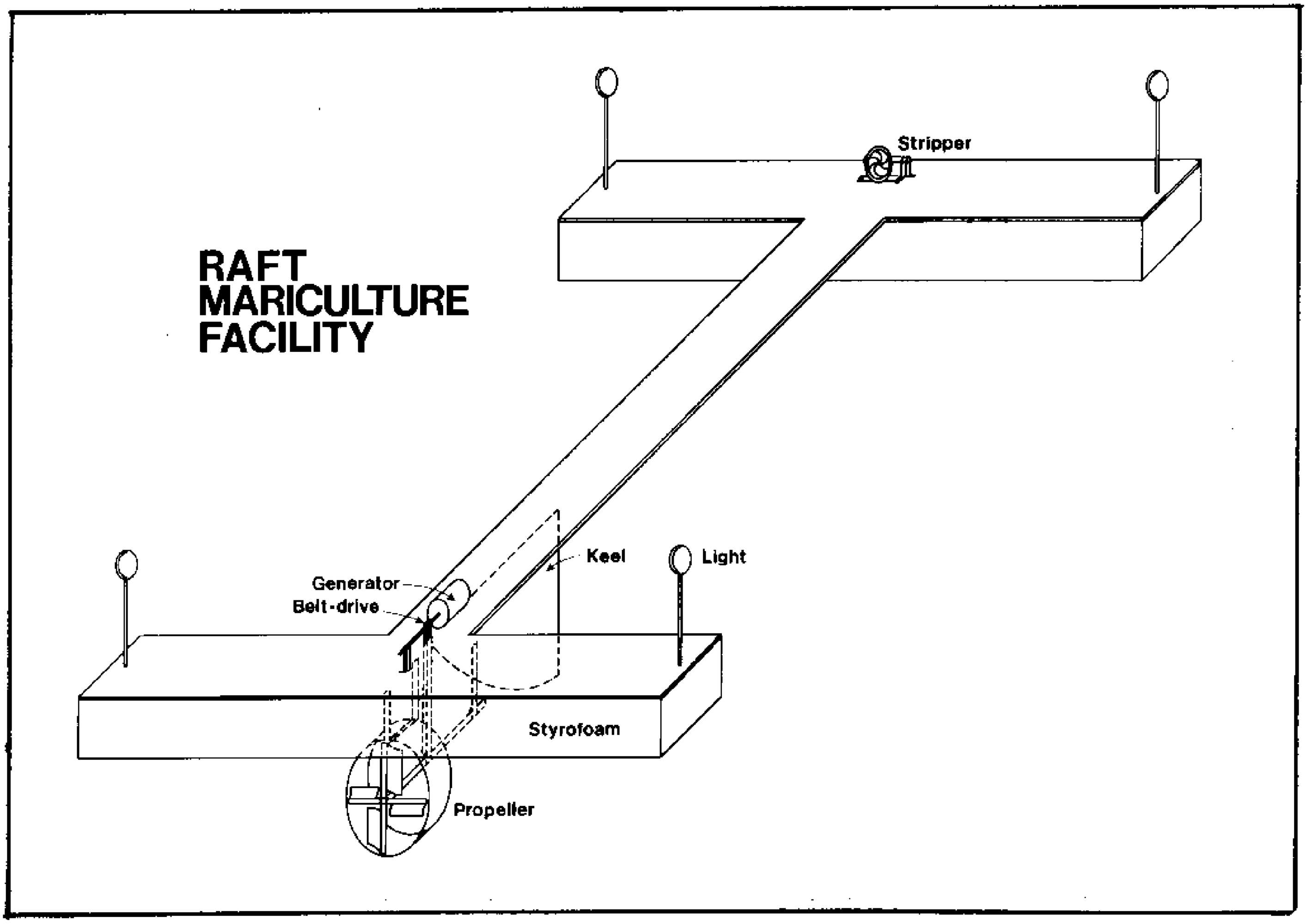

FIGURE 5.1 Basic Design of Frame and Energy-Generating Apparatus

for the structure in tidal currents and keeps it parallel to the shoreline. The energy for the lighting is supplied by a small AC generator which is powered by belt-drive from a propeller and drive-shaft located under the bow. The propeller is turned by current flow from the tidal creek or any other available current. A backup system of 12-volt automobile batteries and DC lamps may be necessary. An alternate DC system would operate through an ordinary automobile generator, a coil, and several storage batteries.

The basic design of the raft facility showing suspended rope substrates is given in Figure 5.2. Thirty-four poles, approximately 5 feet (1.5 m) in length, line the inside of both the bow and the stern. Five ropes are fastened by brass snaps to each pole for a total of 4,420 feet (1381 m) of rope substrate. The surface area of substrate is estimated at 276 ft^2 (26.3 m^2). The stiff, vertical poles provide not only the attachment points, but also a method of adjusting the depth of the ropes. Variation in growth zones is also provided by rope attachment at varying depths. In this manner, polyculture would be achieved for the whole facility, even though an individual rope may be colonized by one or two species.

The stripper is a large working replica of an iris diaphragm (Figures 5.2, 5.3). The diaphragm allows for variation in aperture width and can be adjusted to accommodate varying sizes of rope substrate or to strip varying amounts of seaweed from the rope. The diaphragm blades would be constructed of high-strength sheet aluminum, the remainder of galvanized metal, and the stripper mounted on the stern.

Operation

For harvesting, a boat with catch basins is tied astern of the raft adjacent to the stripper. The ropes are detached singly at the bow end, and the current or a technician carries this end astern. Here the rope is picked up by a hook. The bow end of the rope is then fed through the opened stripper in a manner that would not drag it across the boat (rollers located on the gunwales may be necessary). The bow end of the rope is attached to a hand-operated boat winch for stripping (Figure 5.3). The stern end of the rope is detached when the bow end remains secured. The stripper is then tightened to remove the desired amount of seaweed from the rope substrate. Upon cranking the rope onto the spool of the winch, seaweed is stripped by the diaphragm and falls into a basin positioned below it in the boat. A portable tray is necessary for catching the seaweed and allowing it to be funneled into the basin. The boat is moved to position another catch basin in place when one becomes full. It is also necessary to position different catch basins below the stripper when certain seaweeds are to be kept separate (e.g., single-species agarophytes being kept separate from mixed species of green and brown algae). Using the vertical zonation concept, this separation of species is also maintained by stripping ropes

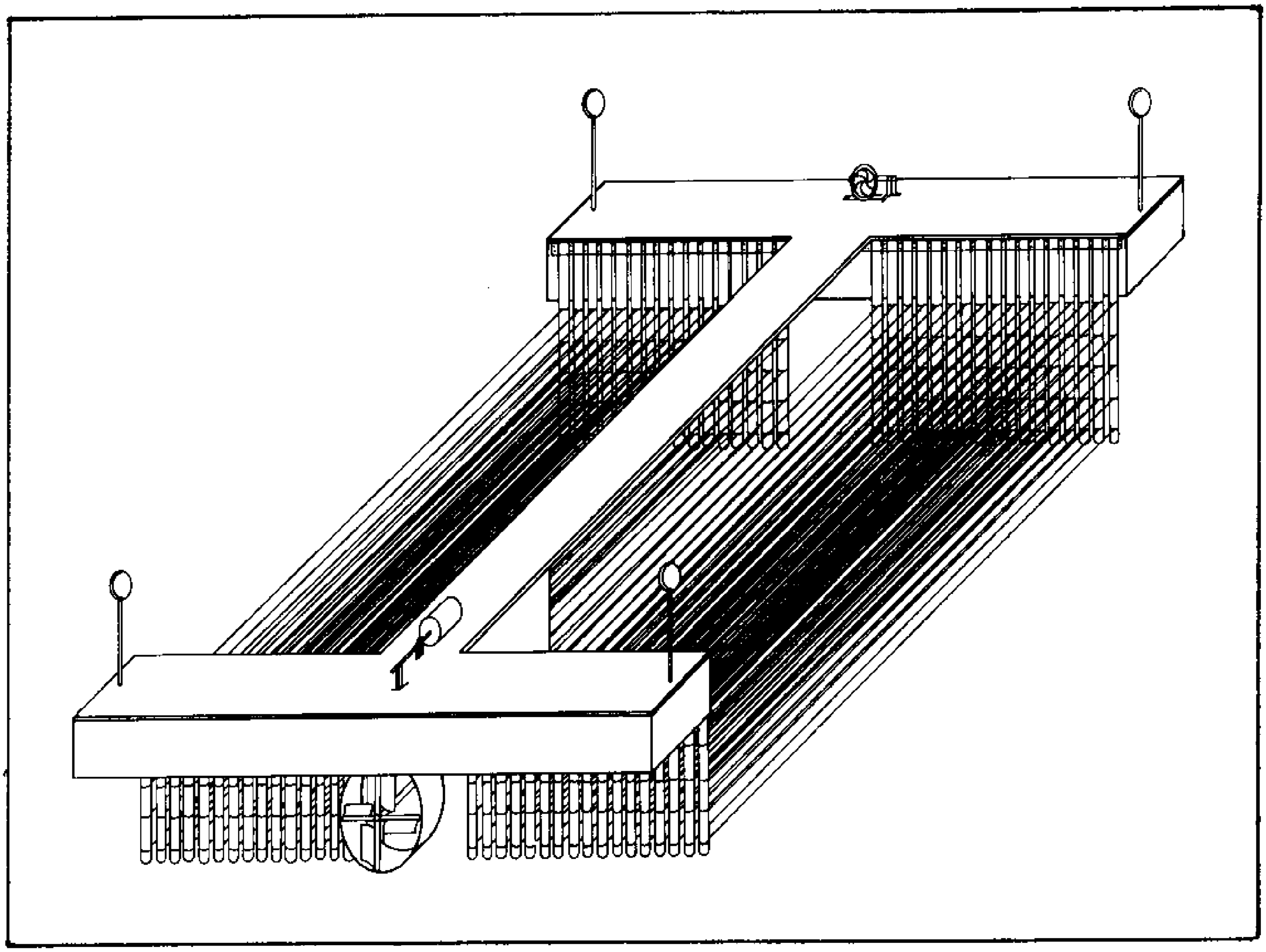

FIGURE 5.2 Attachment of Poles and Rope Substrates

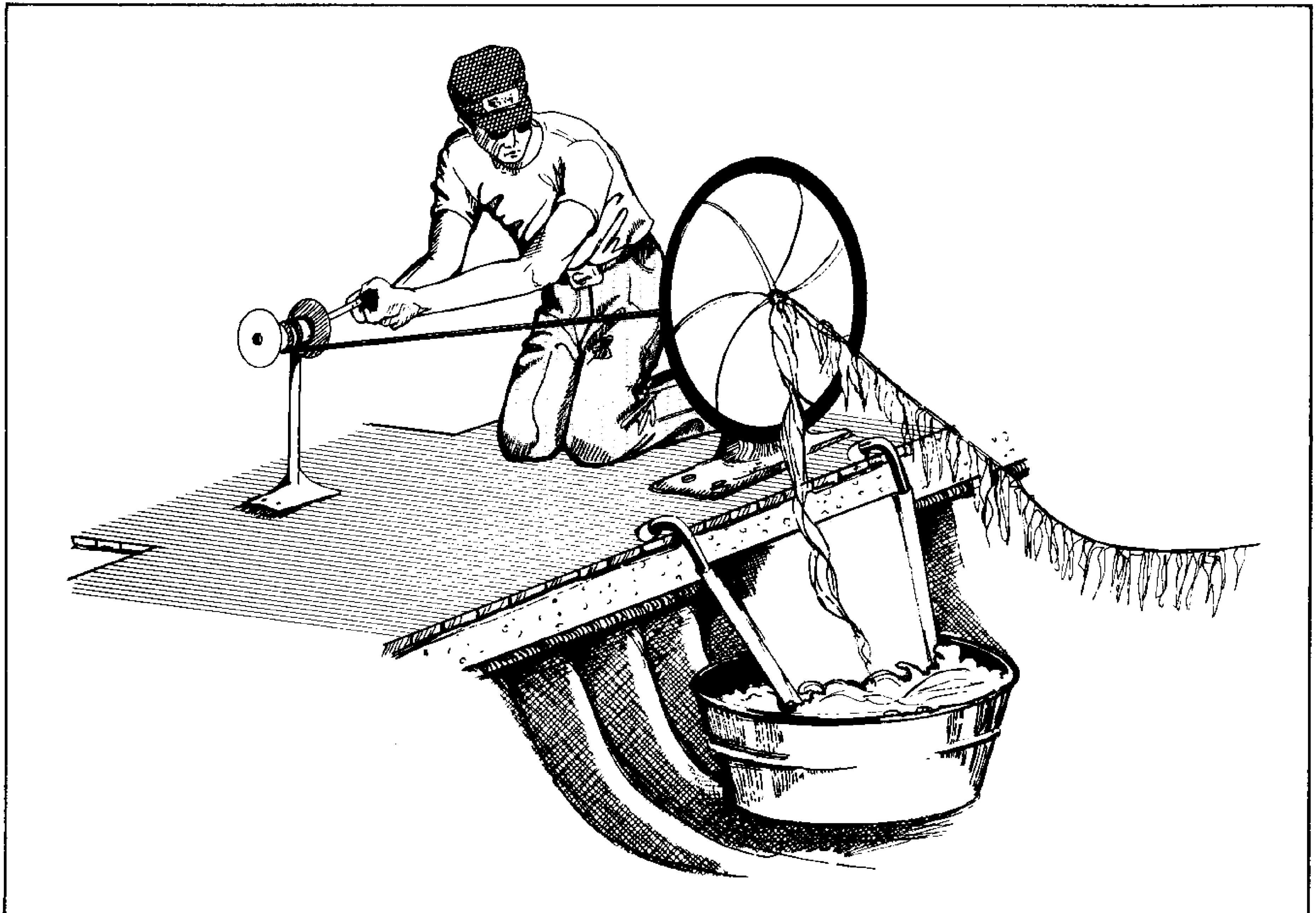

FIGURE 5.3 Use of the Adjustable Stripper

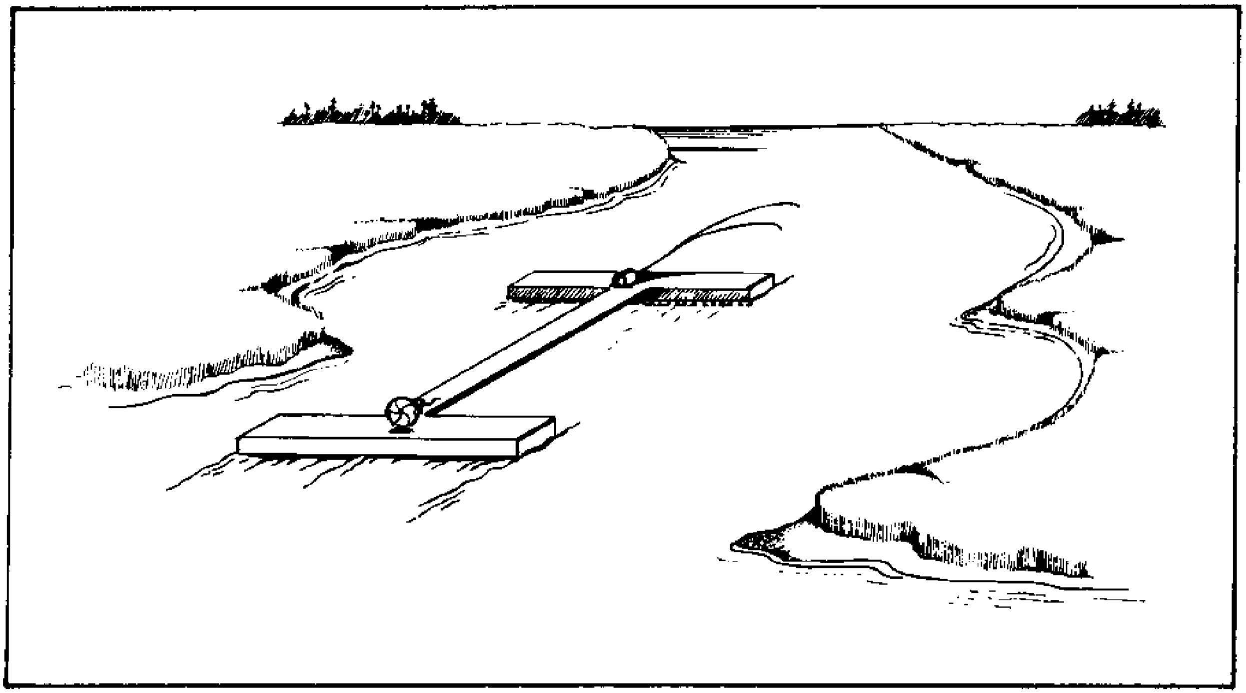

FIGURE 5.4 Mooring of the Raft in a Tidal Creek

attached at the same depth in the same catch basin. Those species growing at certain zones (e.g., Enteromorpha in the upper zones and Sargassum in the lower zones) are kept separate to aid in marketing. In the event all species are to be marketed for methane production, the seaweeds might be indiscriminately mixed in the same basins.

To facilitate removal of ropes attached on the lower parts of the poles, the poles are raised by loosening the brackets holding their upper ends to the raft. Following stripping, the stern end of the rope is pulled from the winch toward the bow and attached there, and the bow end is attached at the same depth on a stern pole.

Figure 5.4 illustrates the mooring of the facility in a tidal creek. Mooring is accomplished by two 11.4 kg (25 lb) COR (plow-type) anchors, each attached to 7 meters of heavy chain. The chains are attached by ropes to the bow of the barge in bridle fashion to enable one anchor to hold during ebb tide and the other to hold during flood tide. When the tide and current direction changes, the raft swings around 180° and faces the incoming current. Harvesting and electricity generation are thus facilitated by always keeping the bow facing the current.

Anticipated Results

Anticipated problems of the proposed facility relate to materials failure and fouling by marine organisms. Metal construction materials will be either brass, galvanized, or marine quality aluminum. Peak periods of oyster spat fouling can be anticipated, and the use of the raft during these periods can be avoided. Because of its proximity to land in the tidal creek setting, the structure can be frequently serviced or drydocked for repairs. Vandalism and fisherman-damage are eliminated by mooring adjacent to private property (RPI's marine laboratory) and by the remoteness of many South Carolina tidal creeks. The method of inoculating the rope substrates is not without problems, but it will not be described here. It will use a combination of field and laboratory sources for plant material.

In summary, the proposed raft culture facility has several adaptations and innovations of design, making it useful in tidal creek/river habitats, energy independent, and simple to harvest.

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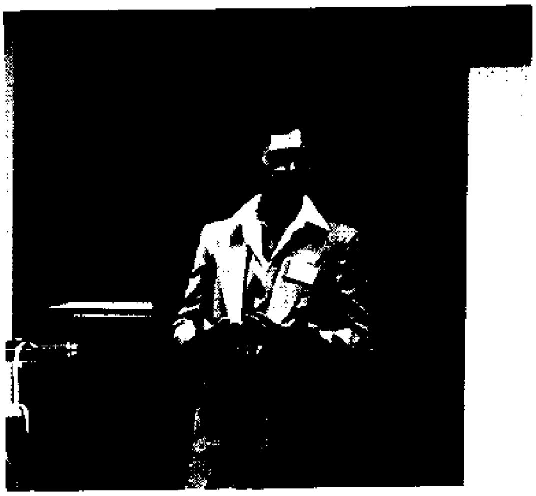

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6

THE NEW YORK STATE MARINE BIOMASS PROGRAM

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Introduction

The New York State Marine Biomass Program was initiated in December 1979 under sponsorship of the Gas Research Institute, New York Energy Research and Development Authority, and the New York Gas Group. The goal has been to demonstrate the feasibility of cultivating marine plant biomass as a feedstock for anaerobic digestion to produce methane for the northeastern United States.

New York State is especially dependent upon imported energy. It is one of the largest consumers of imported petroleum and receives most of its natural gas via pipeline from Louisiana. Recognizing the great potential of marine biomass as a renewable source of synthetic natural gas, established by west coast research, a New York program was initiated.

The initial research centered on screening potential, indigenous seaweed species. The sketchy literature base concerning growth characteristics and chemical composition of seaweeds in the northeast only permitted us to select some likely candidates. It contained very little information useful in mass culture studies.

Nine dominant, indigenous seaweeds were selected initially to provide representation of red, brown, and green algae with a variety of known growth habits. The literature suggested that these candidates (1) were capable of high growth rates, (2) had different seasonal growth maximums, (3) exhibited different attachment requirements, and (4) were capable of either sexual or asexual reproduction (Table 6-1).

TABLE 6-1 Initial Species Chosen for Study in the New York Marine Biomass Program

Species	Growth habit	Reproduction
Chlorophyta		
Codium fragile	attached, floating	sexual
Ulva rigida	floating	sexual, vegetative
Phaeophyta		
Ascophyllum nodosum	attached, floating	vegetative

Fucus vesiculosus	attached, floating	sexual, vegetative
Laminaria saccharina	attached	sexual
Rhodophyta		
Agardhiella tenera	attached, floating	sexual, vegetative
Gracilaria tikvahiae	floating	vegetative
Chondrus crispus	floating	sexual
Palmaria palmata	attached	sexual

A culture facility, constructed during the spring and summer of 1980, was designed to permit the study of potential species in dense tank cultures under light, temperature, and nutrient conditions typically found in Long Island waters. The greenhouse (Figure 6-1) is supplied with unfiltered, running seawater at ambient temperature and nutrient levels. During the screening study, which lasted until summer 1981 (a full year's growth data for all species), four cultures of each species were grown. Two replicate cultures received ambient water at a rate of 20 volumes per day and two others received water at 2 to 4 turnovers per day supplemented with ammonium nitrate to maintain nitrogen levels of at least 30 micromolar. This was done to crudely determine whether nitrogen limitation of seaweed growth occurred. A variety of other experiments were conducted to assess the effects of light intensity and density on growth (yield). All cultures were weighed at least weekly to determine the seasonal profiles of growth. Samples of seaweed material from culture and field collections were sent to the General Electric Company for compositional and methanogenesis analyses. Preliminary field experiments were conducted on growth of some candidates on raft-like structures and in cages covered with different mesh sizes, both grown at several depths.

The data obtained from this research were evaluated at the end of summer 1981 and a shortened list of species was drawn up which included *Laminaria saccharina*, *Gracilaria tikvahiae*, *Agardhiella tenera*, *Codium fragile*, and *Fucus vesiculosus*. These data resulted in the finding that no one species would suffice. Rather, a multiple-species concept was put forward which postulated a cold-water, or winter, crop and a warm-water, or summer, crop. The use of multiple species for biomass production is required by the extremes of temperature experienced in northeastern waters. This concept required considerable adaptation of the research and development program, for the primary target species have very different growth modes and reproductive cycles.

Laminaria was the only species of the short list to exhibit significant growth during the late fall, winter, and spring. Growth rates of this species approached 6 percent per day, but considerable plant-to-plant variability was observed. *Gracilaria*, *Agardhiella*, and *Codium* grew best during the summer months. Of these three, the two red species grew at 6 to 8 percent per day in mid-summer. *Codium* grew at rates up to 4 percent per day. Both *Agardhiella* and *Codium* cultures exhibited sexual reproduction during the late summer and early fall; *Gracilaria* is strictly vegetative. Cultures of *Fucus* exhibited a bimodal growth peak--

FIGURE 6.1 The Greenhouse

spring and fall. This floating species presented some difficulties during the summer because of high temperature and light conditions while exposed at the surface of the tanks. It is, however, the best-represented species in the literature. On a dry weight basis, all species exhibited attractive compositional features and methanogenesis capacity. In fact, most of the theoretical gas yields exceeded that of the preferred west coast species, *Macrocystis pyrifera*. Only *Codium* fared poorly on a wet weight basis because of its high water content (92 to 94 percent).

Research in New York s marine biomass program has been, to date, primarily biologically oriented. Field studies using nearshore rafts have been initiated, but the informational requirements have been principally met with laboratory culture experiments. Marine biomass production uniquely requires development of substrates upon which the crop can be cultured on a very large scale. The New York biomass program has shifted its focus toward development of growth substrates meeting local requirements fostering larger-scale plant production and experimentation. Principle local requirements for such a substrate are:

1. Suitability for use with two (or possibly more quite different seaweed growth forms
2. Ability to withstand a wide range of environmental conditions including storms and sea ice
3. Ensuring that substrates are unattractive to vandalism in a heavily utilized coastal region

A series of steps have been defined by which the development of appropriate structures, by engineers, will be undertaken. These steps are premised on the concept of modularity, which allows scaling up of size of structures as the biological capability to cultivate increasing numbers of plants emerges.

Field Experiments

During fall 1982, field cultures of *Laminaria* were initiated on small rafts anchored to the sea floor in 1.5 and 2.5 meters of water (Figure 6-2). Plants were fastened to 15-centimeter-long pieces of rope that were in turn attached to PVC rods. By mid-December, plants attained an average length of about 75 centimeters. No plants were lost during several storms that produced waves as high as 1.5 meters. Rafts could not be visited from the end of December to the end of January because of ice and heavy winds. During the first week of February, observations indicated that plants were not lost from the rafts. They had grown to a total average length of about 90 centimeters. Some plants on the shallow raft exhibited fraying at the edges of the blades. Also, these plants experienced more entanglement with the raft frame, probably because this raft is in the surge zone. The plants on both rafts grew at rates comparable to those in the greenhouse cultures, but did not attain similar lengths. Field

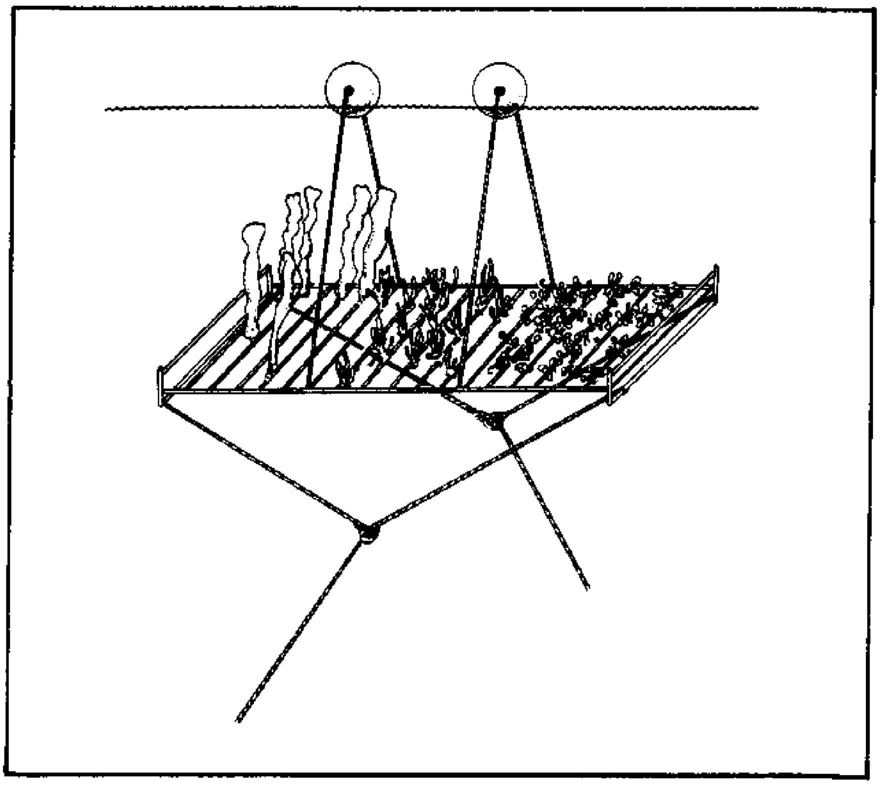

FIGURE 6.2 Typical Bed-Frame Raft Used in Field Culture

plants only grew to lengths of about 2 meters because of greater erosion of blade apexes. This is partly attributed to the specific design of the raft.

Observations on raft plants indicated that some were producing sori as early as the beginning of April. However, no reproductive plants were seen in natural beds at the same time. Toward mid-May, some reproductive material was noted at the Crane Neck site where the rafts are deployed. By mid-May there were young sporophytes attached to parts of the raft frames. These were probably recruited from fertile material growing on the PVC frames.

We also initiated a recruitment study in early April. Concrete blocks were placed near both rafts and these were periodically being removed for microscopic examination to determine the presence of gametophytes and young sporophytes. Other materials, including rope, are also attached to the rafts as settlement surfaces.

A harvesting experiment similar to the one in the greenhouse is also in progress at the Crane Neck field site. A high and low density situation was created by moving plants attached to stones naturally onto a marked-off area. Plants are being harvested to 50-centimeter lengths on the same frequency schedule as in the greenhouse, 4, 6, and 8 week schedules.

By the end of May, plants still looked healthy and we expect that we will have some survival of plants on the rafts through the summer period. As plants exhibit reproduction, sorus material will be sampled and brought to the environmental chamber for cultivation.

This summer we are planning to use *Codium* and *Gracilaria* material attached to ropes/PVC rods on the rafts in space not occupied by *Laminaria*. Individual plants will be twisted into three-strand polypropylene rope. The *Codium* is obtained from nearby populations while vegetative *Gracilaria* has been obtained from Florida. We hope to obtain sexual material from trawls in local waters, as well as from Florida.

Test Farm Design Options

Engineering in the New York State Marine Biomass Program began with senior students' design products addressing problems associated with modular raft designs and their mooring systems. A full time engineering effort then commenced examining the entire range of engineering aspects of the project.

To design the biological-engineering experimental farm (BEEF) to be deployed in 1983, design requirements needed to be specified. Some of these requirements are beginning to be understood as results are obtained from field experiments. At the proposed test farm sites in Long Island Sound, water depth is 50 to 60 feet and the tidal current runs from 1 to 1 1/2 knots. Wave data, available from the Coast Guard, indicate a design wave of four foot height with a period of three seconds. A maximum design wave of nine and one half feet is based on visual observations during the April 1982 blizzard.

Biofouling rates and type data are based on research from the literature for areas in Long Island Sound. These have enabled design of experiments to study biofouling on the candidate materials and coatings to be used on the test farm. Emphasis is placed on developing methods to minimize biofouling on the structure. Many documented methods of minimizing biofouling are based on the use of copper or chlorine containing substances or other paints which may be toxic to the seaweeds growing on the raft. Mechanical methods of biofouling prevention appear encouraging and are being explored.

Materials performance and degradation is being addressed from both the bioengineering aspect of the plant/material interaction and from a structural aspect. Materials selected for the plant substrate will be thoroughly tested for corrosion/material degradation, loss of mechanical strength and plant/structure compatibility.

Among the more important design considerations which have emerged are:

1. compatibility of materials with the plants
2. floatation/damping and anchor systems
3. ease of fabrication and deployment
4. ease of maintenance of the structure including repair and biofouling prevention
5. ability to vary the depth of the growing substrate from 1 to 4 meters below the surface

A biological and engineering experimental farm must be conducive for both the biological and engineering research. Clearly defined areas for the plants, boat and diver access, as well as ease of instrumentation must be provided. The designs must also provide a vision towards expansion and enlargement.

Plant/structure interaction investigation began with analysis of the seaweed in the fluid environment. Specifically, how do plants, individually and as a group, behave when subjected to different wave and current conditions? For individual plants, the breaking strength of the different parts of the plant are being determined. For Laminaria, for example, the breaking strength of the blade, stipe, and holdfast are being determined. Other influencing factors such as the age and condition of the plants are being considered. Several questions arise that will have to be answered in field tests: How does the ultimate strength differ as a result of various growing conditions? Does severe handling of the plants require recovery time?

A flow test tank has been constructed which has a viewport through which visual observations and photographic recordings may be taken. Preliminary tests include determination of breaking strength in laminar and turbulent flow for the blade, stipe, and holdfast of Laminaria; acceleration of the plant with the current; the effect of defects in the plant; and tangling of plants in the flow stream. Because of the many variables, a coherent test program is being planned.

Materials degradation is being addressed over a broad front rather than for one particular design or development concept. The behavior of the materials when subjected to stress in the marine environment as well as the effects of biofouling are being evaluated in several test series: rope corrosion and coating tests are being performed under laboratory conditions as well as in the field. Preliminary results of the rope tests, done in accordance with Cordage Institute Standards, show that strength may be reduced by up to 60 percent after exposure of 4 months in Long Island Sound. Biofouling of rope is also being examined. Corrosion and coating tests are being coordinated for several structural materials to determine their corrosion protection as well as their suitability for antibiofouling measures. Toxic substances have not been considered due to their effect on seaweeds. Polymer coating as well as thermally applied metallic coatings are being tested in field and laboratory.

Three design concepts have been developed:

Short H

The Short H concept (see Figure 6-3) is based on the design of seaweed farms in the Orient. It is modular, each module being 100 feet long and 32 feet wide. The 4 foot width is a comfortable reach for a person. Therefore, there are 8 foot wide rope culture areas separated by 8 foot boat lanes. Two boat lanes and two rope culture areas give a width for each module of 32 feet.

Each module has two buoys connected by cable allowing the depth of the module to be easily varied. The buoys are a cylindrical cross-section with provisions to allow the density of the buoy to be varied. Thus the damping of the structure to wave motion can be easily varied to suit the age and condition of the plants.

The buoy attachment points are at the edges and ends of the module allowing a hinge-like movement between modules. Adaptations of existing articulated joints in the marine industry will be used. Some features of present popular joint designs must be changed, however, to eliminate petroleum based lubricants which may be harmful to the plants. Solid lubricants such as the wide range of available engineering plastics may be substituted.

The Short H allows both horizontal and vertical rope culture methods. Since the plants must be weighed and measured, on a regular basis, it is important that easy attachment and removal of the ropes be provided. Several attachment schemes are being

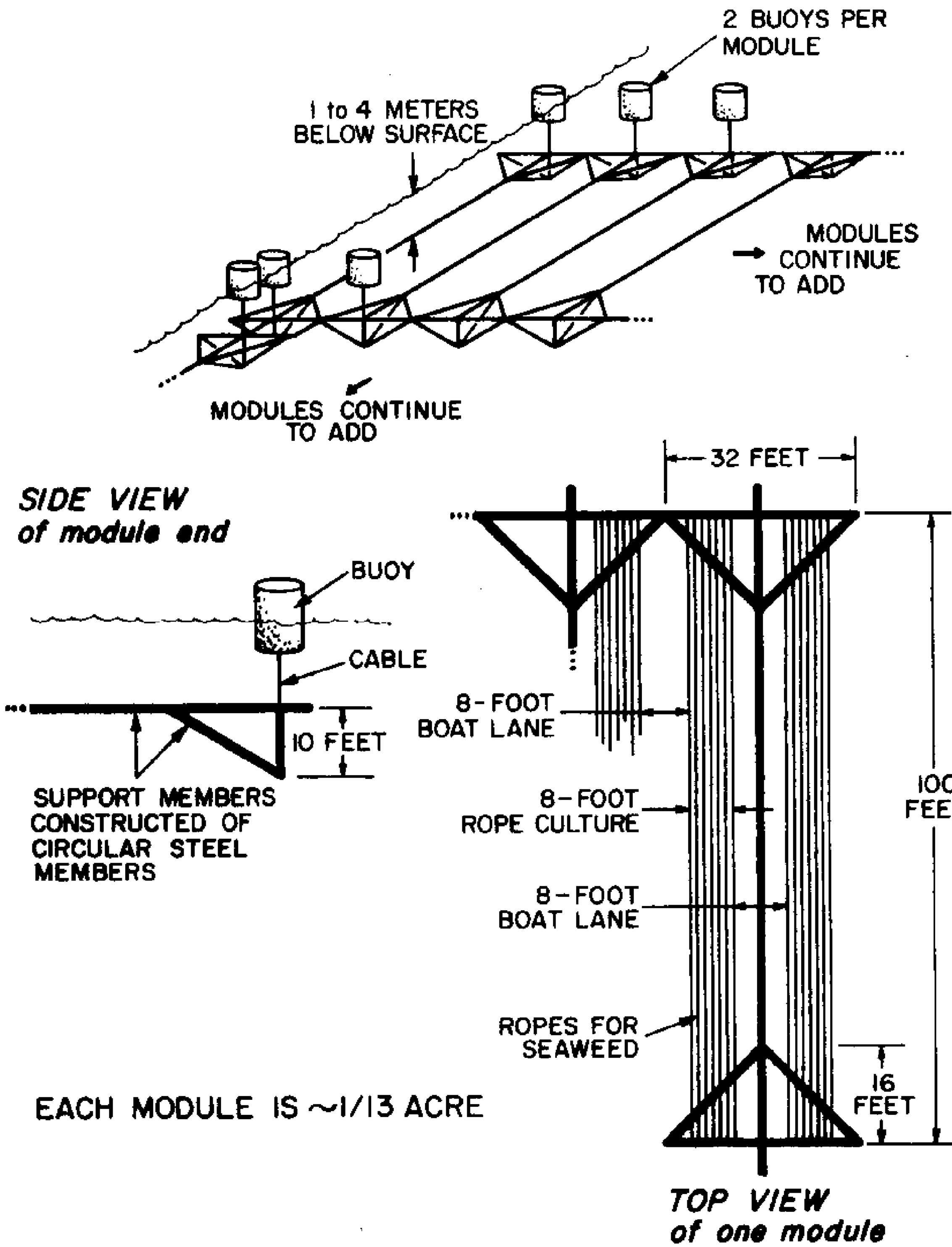

Figure 6.3 The Short H Design

investigated. An arrangement that uses no special tools and can be utilized by both divers and researchers from a floating platform is sought.

Structural members of the Short H are 8 inch round hollow cross sections. The candidate material is hot-rolled welded steel. Alternate structural members are cold formed welded structural steel tubing of square cross section. The material for both types of members is American Society for Testing and Materials specification A500, Grade B and is available in continuous length, splice-free up through 100 feet. Calculations performed at Cornell show that for the expected wave spectra, the stress is below the fatigue limit.

Hex

This concept (see Figure 6-4) consists of equal length members connected to buoys at both end points and center. The buoys are attached directly to the members and rely on a water ballasting scheme to change the depth of the substrate. The depth of the structure is varied by filling the internal tubes with water, sand, or other suitable material, and by the amount of ballast. Density of the buoy and thus the damping of the structure is determined by the type of fill material and ballast. The design shown is the first iteration of the Hex using structural members of triangular cross-section with articulated joints. The figure shows a diagrammatic representation of an articulated joint. The actual joint would be drawn from current marine industry joints similar to those described for the Short H. Current thinking for the Hex suggests circular members joined solidly to the buoys. Horizontal and vertical rope culture methods could be utilized as well as several types of netting. Attachments to remove the ropes and netting are similar to those developed for the Short H.

Several of the Short H and Hex features are interchangeable including the cable and buoy arrangement and methods of buoy construction. Mooring and anchoring of both structures would consist of lines from the buoys in the Hex and the lower vertices of the Short H to a mass on the bottom. The mass is anchored by three anchors 120° apart or four anchors 90° apart to prevent the mass from dragging under loads.

Jack Up

This concept (see Figure 6-5) borrows heavily from the offshore oil industry. Three piers support a triangular base for the individual growth frames. Individual piers are round cross-section steel or on appropriately reinforced concrete. Horizontal members of standard space frame construction are attached to the mechanical actuators on each of the three piers. Depth is controlled by a combination of floatation and mechanical actuator systems. The anchoring of the piers is accomplished by either driving the piers into the bottom or by attaching the piers into a ballast mass.

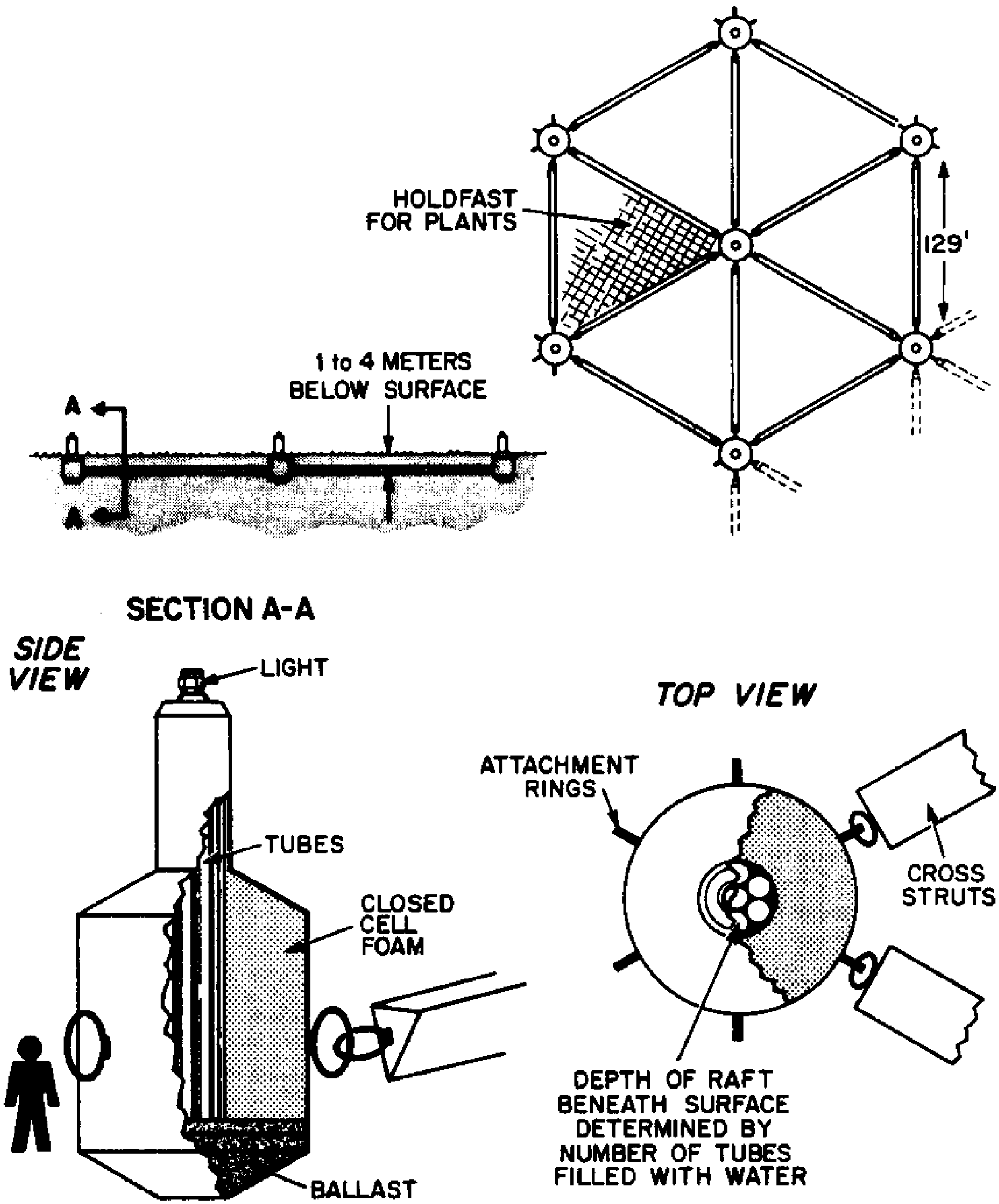

Figure 6.4 The Hex Design

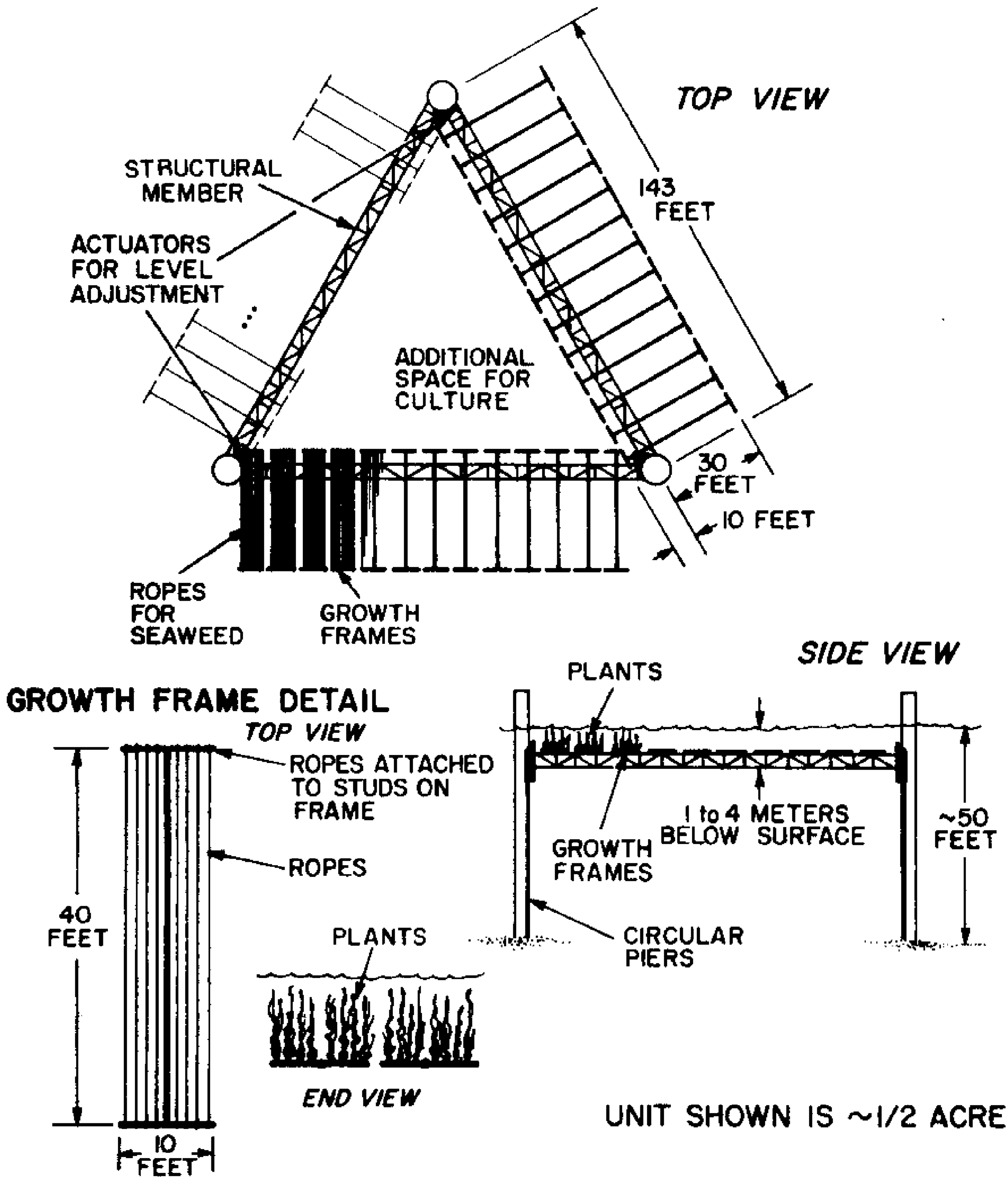

Figure 6.5 The Jack Up Design

The Jack Up uses individual growth frames that would be removed as a unit to measure and weigh the plant. This system could use rope or netting attached directly to structural members. Advantages offered by the Jack Up are that it rests directly on the ocean bottom adding stability to the structure, eliminating the need for a floating work station and reducing damage from vandalism because of the imposing size of the structure.

Performance Analysis For the Short H

To ensure sound engineering design, a performance analysis was carried out. The general procedure for the analysis is outlined as follows (for a complete discussion of the analysis consult the publication listed in the Postscript of this chapter):

1. Determination of environmental forces; waves and currents
2. Structural analysis (quasi-steady state); stresses and displacements
3. Mooring system analysis
4. Dynamic analysis of the entire system

Some preliminary results of the structural analysis of the Short H under the quasi-steady state condition will be presented. As shown in Figure 6-6, a single module of the Short H is used for the investigation. The mooring system analysis and the dynamic analysis have not yet been performed, but will be in the near future.

Design Conditions

To compute the wave forces acting on the farm structure the design wave conditions must be specified. Wave data near the proposed site were obtained from the Coast Guard and the following values used:

H = wave height = 10 ft
T = wave period = 4 sec

The water depth, h, near the proposed site is roughly 53 feet. We assume that the wave environment can be described by small-amplitude monochromatic waves, that is,

$$\eta = \frac{H}{2} \cos \left(\frac{2\pi}{L} x - \frac{2\pi}{T} t\right)$$

where η is the free surface displacement and L is the wave length, which can be determined from the dispersion relation.

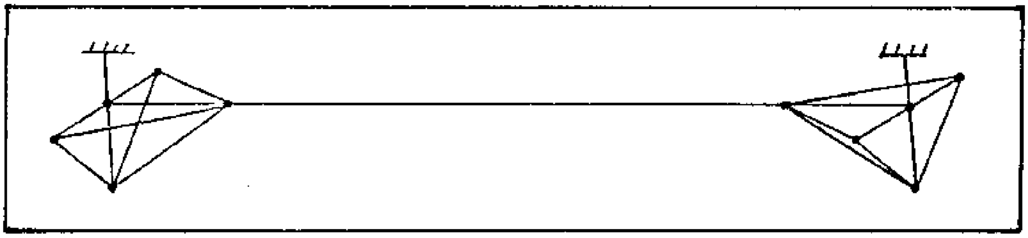

FIGURE 6.6 Sketch of a Module of the "Short H" Structure

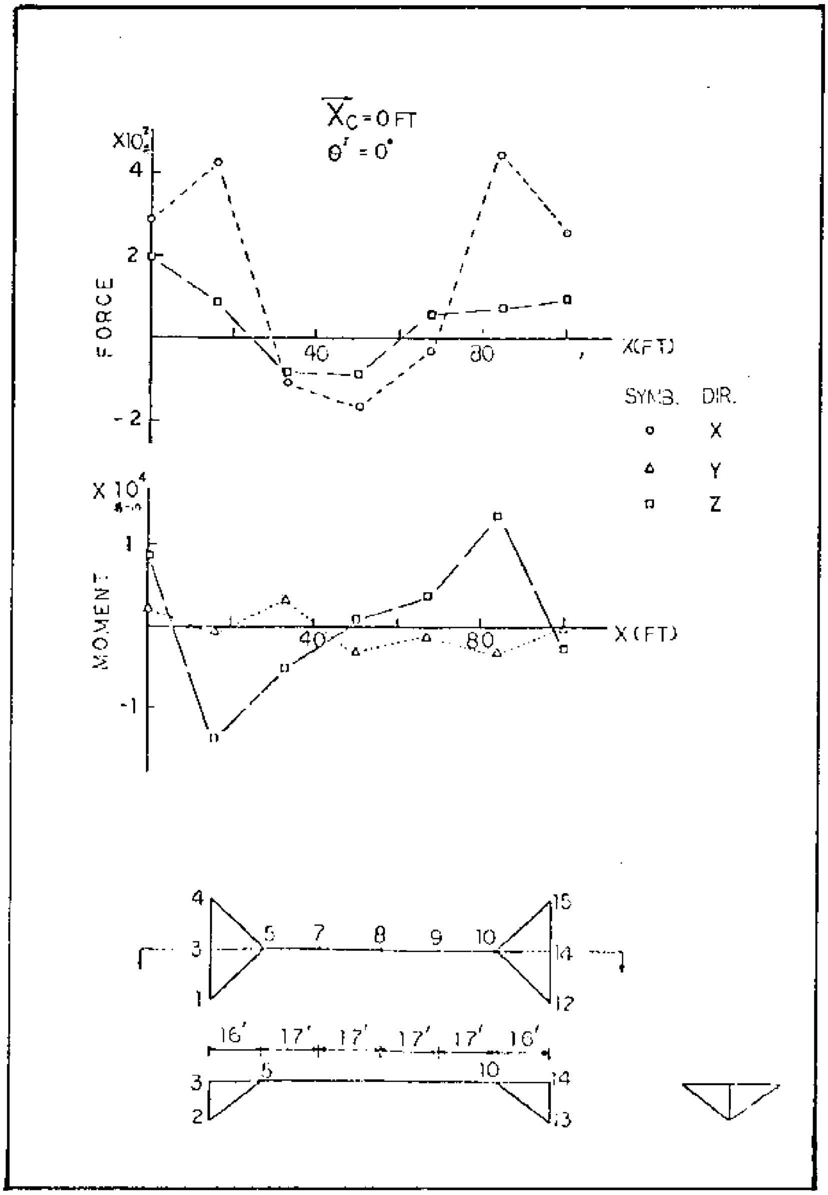

FIGURE 6.7 Force and Moment Distribution

Thus,

$$\left(\frac{2\pi}{T}\right)^2 = g\left(\frac{2\pi}{L}\right)^2 \tanh\left(\frac{2\pi h}{L}\right)$$

Using the design wave period and water depth, we find that the design wave length is L = 82 feet.

The farm structure is assumed to consist of 8-inch steel pipes with inner diameter of 7.5 inches. The Young's modulus is 29.5×10^6 psi. In numerical computation, the farm structure is fully submerged in the water with the submerged depth 6 feet. As shown in Figure 6-6, the structure is suspended by two steel cables.

Wave Forces

Since the diameter of the steel pipe is rather small compared to the design wave length, the Morrison's formula is used for computing the wave forces (Ippen 1966). Thus

$$\vec{f} = C_m \rho \frac{\pi D^2}{4} \frac{d\vec{u}}{dt} + \frac{1}{2} C_D \rho D \vec{u}|\vec{u}|$$

where $\vec{f}$ = the wave force per unit length; u = the fluid particle velocity; du/dt = the fluid particle acceleration; ρ = the density of the fluid; D = the diameter of the pipe; C_D = drag coefficient and C_m = mass coefficient. Both the drag coefficient and the mass coefficient depend on the Reynolds number, Re = Umax D/υ, where υ is the kinematic viscosity of the fluid and U_{max} is the maximum wave orbital velocity. According to the Shore Protection Manual (CERC 1973), the following values can be used for the mass coefficient:

$$C_m = \begin{cases} 2.0 & , \ Re < 2.5 \times 10^5 \\ 2.5 - \dfrac{Re}{5 \times 10^5} & , \ 2.5 \times 10^5 < Re < 5 \times 10^5 \\ 1.5 & , \ Re > 5 \times 10^5 \end{cases}$$

On the other hand, the recommended values for C_D are plotted in Figure 7-58 of the Shore Protection Manual.

Once the force distribution along each member of the farm structure is obtained, it is converted into the concentrated forces and moment acting on each nodal point. A typical force and moment diagram is shown in Figure 6-7. In this case the direction of wave propagation is parallel to the major axis of the structure and the wave crest is located on the left-side edge of the structure. Various situations with different angles of wave incidence and different positions of the wave crest are computed. The total vertical and horizontal forces are summarized in Figure 6-8.

θ^I \ POSITION OF WAVE CREST (FT)		0	10	20	30	40	50	60	70
0	H	2457	1664	-462	-2077	-2476	-1606	529	1976
	V	3959	1187	244	-75	-359	-1187	-244	75
$\pi/4$	H	452	-851	-1519	-1537	-434	952	1848	1479
	V	389	314	-348	-389	-314	348	382	1465
$\pi/2$	H	2553	-62	-2294	-3182	-2553	-34	2294	3278
	V	1465	708	-35	-708	-1465	-708	0	708

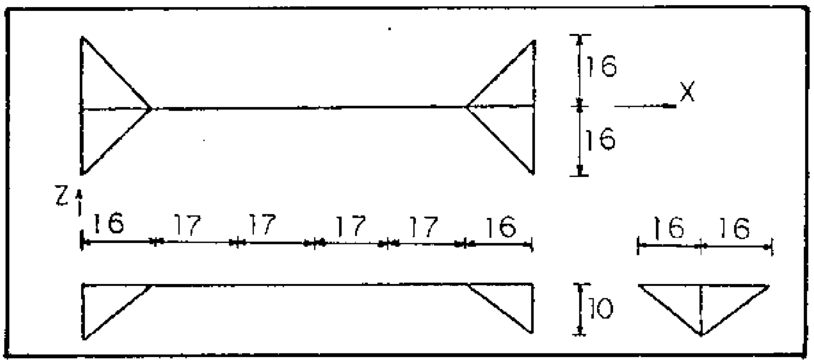

FIGURE 6.8 Total Horizontal and Vertical Forces versus Position of Wave Crest in the Wave Direction

Structure Analysis

The calculated wave forces and moments are used as input data for computing the stress distribution along the structure and the displacements and the rotations of the structure. Again, different angles of incidence and positions of wave crest are tested. Some typical displacements and rotations of nodal points along the structure are shown in Table 6-2. In this case the angle of incidence is zero degree and the wave crest is parallel to the left edge of the structure. In Table 6-2, the displacement is read in inches and the rotation is measured in degree. For various combinations of incident angles and the wave crest location, the maximum stress is summarized in Table 6-3.

The maximum stress is about 6,000 psi, which is much smaller than the yield stress for the steel.

References

Coastal Engineering Research Center. 1973. Shore Protection Manual.

Ippen, A.T. 1966. Estuary and Coastline Hydrodynamics. McGraw-Hill, New York.

Postscript

As a result of discussions at the workshop and subsequent design reviews, the New York Marine Biomass Program developed a fourth design option which was placed in Long Island Sound in September 1983. The design incorporates elements of Chinese and Japanese seaweed farms (Figure 6-9). Further information on the Oriental-style design and a final performance analysis of the Short H is available in:

Squires, D.F. and L.B. McKay, Marine Biomass: New York State Species and Site Studies, 1982 Annual Report, New York State Energy Research & Development Authority, Albany, NY, 1983.

Performance analysis for the Oriental-style design is available by contacting:

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TABLE 6.2 Displacements (in inches for 3 dimensions: X,Y,Z) and Rotation (in radius for 3 dimensons: XX,YY,ZZ) of Nodal Points

Node load	X	Y	Z	XX	YY	ZZ
1	6.519E+00	3.076E-01	-1.356E+00	7.08E-03	-7.77E-03	3.45E-02
2	1.034E+00	1.155E+00	2.824E-04	7.07E-03	-9.38E-03	3.35E-02
3	6.518E-03	3.074E-01	1.543E-04	6.77E-03	-4.19E-03	3.13E-02
4	-6.510E+00	3.076E-01	1.357E+00	7.23E-03	-8.04E-03	3.47E-02
5	4.461E-03	6.823E+00	1.648E+00	6.98E-03	-1.04E-02	3.39E-02
6	0.000E+00	0.000E+00	0.000E+00	0.00E+00	0.00E+00	0.00E+00
7	2.811E-03	1.302E+01	4.224E+00	6.99E-03	-1.16E-02	2.43E-02
8	1.162E-03	1.589E+01	5.517E+00	7.01E-03	3.74E-05	2.27E-03
9	-4.879E-04	1.377E+01	4.212E+00	7.02E-03	1.17E-02	-2.24E-02
10	-2.138E-03	7.455E+00	1.646E+00	7.04E-03	1.02E-02	-3.67E-02
11	0.000E+00	0.000E+00	0.000E+00	0.00E+00	0.00E+00	0.00E+00
12	-7.127E+00	3.304E-01	-1.443E+00	7.48E-03	8.40E-03	-3.80E-02
13	-1.030E+00	1.233E+00	2.737E-04	7.54E-03	9.62E-03	-3.68E-02
14	-4.166E-03	3.302E-01	1.546E-04	7.24E-03	4.13E-03	-3.42E-02
15	7.123E+00	3.304E-01	1.444E+00	7.51E-03	6.81E-03	-3.81E-02

TABLE 6.3 Summary of Maximum Stresses (in psi) and Their Location

θ^{I}	(PSI) $\vec{X}$ (FT.)	0	20	40	60
0°	Max. psi Nodal no.	1,000 (3)	800 (8)	1,600 (5)	800 (8)
45°	Max. psi Nodal no.	2,300 (5)	2,300 (5)	1,400 (10)	1,600 (10)
90°	Max. psi Nodal no.	6,100 (8)	2,900 (8)	6,100 (8)	2,900 (8)

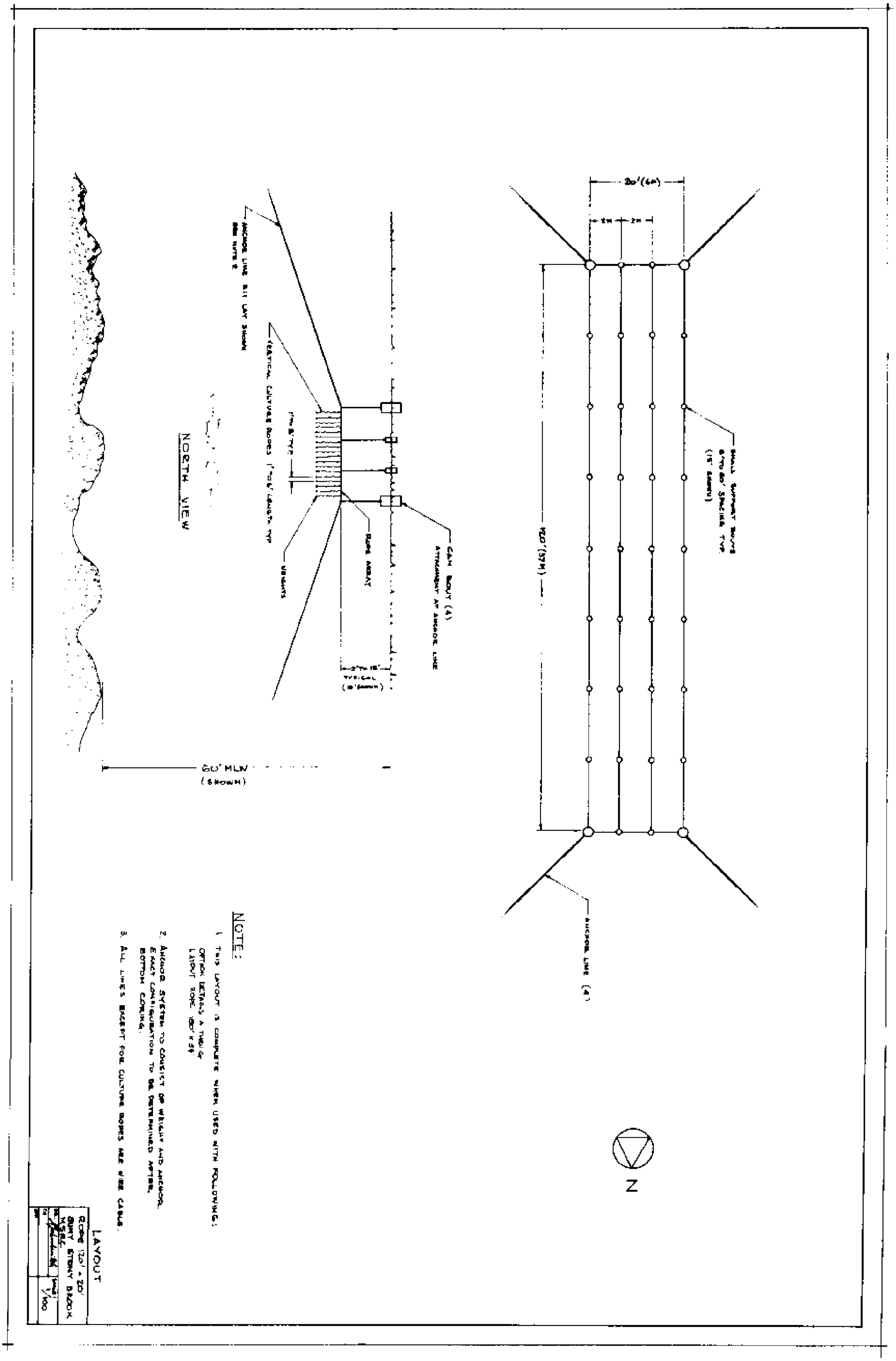

Figure 6.9 Biological-Engineering Experimental Farm Design

SUMMARY

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While the primary purpose of the Workshop on Raft and Farm Design was to develop criteria useful in evaluating designs for macroalgal farms, an added value for participants and sponsors lay in the informal exchange of ideas which occurred throughout formal and informal portions of the workshop.

It is impressive to see how much well-developed work on the artificial culture of macroalgae exists in the United States. A broad array of species are being grown for food, for natural products, and as a source of energy. This breadth of experience is revealed in the papers presented at the workshop and included in this volume. These reports do not purport to exhaustively represent all of the work being done by algal culturists. By the same token, it is clear that experimentation on macroalgal culture is dominated by the biological profession. Few of the substrates or structures used for cultivation of seaweeds discussed at the workshop had been developed with participation by engineers. Similarly, although identifying algal culturists was not difficult, locating engineers with experience in the design or construction of rafts or other devices for the culture of marine animals or plants was extremely difficult. It is hoped that this state of affairs will soon change and that engineers will take greater interest in the design of low-cost substrates; in low-technology solutions to the problems of providing substrates for marine organism cultivation; and in the improvement of materials available for substrate construction.

The workshop was particularly fortunate in having Dr. X.G. Fei, as a participant. Dr. Fei, in addition to bringing to the workshop the experience of the California Macrocystis workers, was able to provide provocative insights into Oriental culture techniques not previously shared by participants. In retrospect, that new knowledge had a far-reaching effect upon the workshop and upon decisions now being taken by the New York State Marine Biomass Project.

Oriental experience with rope culture represents, in some ways, one extreme of the state-of-the-art of macroalgal culture. This approach represents a slowly evolved, pragmatic, low-cost solution to the problems of Laminaria, Porphyra, and Macrocystis culture. But this solution is achieved, in practice, with a concomitant high cost in human effort, for the culture technique is labor intensive. Yet the pragmatism of the solutions and techniques derived in China and Japan cannot be avoided and must be factored into engineering solutions to the US problem of developing culture techniques that are not labor intensive and are highly mechanized.

A thread running through engineering discussions throughout the workshop was the role of engineers in plant aquaculture. Also debated was the status of such studies within the engineering profession. Most academic institutions emphasize high technology in their engineering curriculum; most modern engineering is high technology in content. Can design, review, construction and experimentation with low to medium technology, such as is challenged by macroalgal culture, be made attractive to the engineering student and profession? If not, must a new kind of "engineering" professional be developed?

Finally, the workshop in general highlighted the pressing need to establish better working dialogues between marine biologists and their engineering counterparts. The gap between the two groups in understanding of problems, of needs, and in vocabulary remains too great. As long as biologists are loath to seek assistance from engineers, or, in seeking, have been rebuffed, active cooperation of the two disciplines will be inadequate. Too often, engineering solutions will be done by biologists; or, the biological imperatives will remain unaddressed by engineers.

Exemplary of that gap in communication is a typical (but hypothetical) introductory dialogue between biologist and engineer, which might commence:

Biologist: We need help in designing a substrate which will survive in the wave climate in our bay.

Engineer: Fine. What is the design wave height? What is the breaking strength of the plants?

Biologist: I don't know.

Typically, the discussion terminates at that point.

An understanding of the engineering parameters of the macroalgae is not something which the biologist, in the normal course of his or her research design, would develop. Yet such parameters are the basic working data for the engineer. Engineering involvement in raft and farm design would result not only, perhaps, in better-designed, more functional structures, but, most important, would establish an agenda of new questions to be answered either by biologists or by engineers. In either event, the questions would be raised.

It is in this context that the Workshop on Raft and Farm Design advanced its conclusions, not only in setting out the criteria below for evaluation of a design, but in the delimiting of the kinds of knowledge required both for the design and for its evaluation.

The members of the workshop concluded that an experimental farm structure--for we are far from designing a farm itself--should address the following:

1. Flexibility of use and of experimental design by being able to provide substrate for a variety of species under a variety of ambient conditions of light (as a function of penetration through the water column) and density of plants

2. Ease of access for experimenters, particularly divers

3. Protection from vandalism, which is apt to be a problem in the nearer-shore waters where experimental farms would be located

4. A design sufficiently open to avoid plant damage through chafing or entanglement, yet not so open as to be inefficient

5. A design which produces minimal vertical movement, for acceleration through the water column is apt to be more severe to plants than currents

6. Allow for sampling of plants within the structure without destruction of the structure or portions of it

7. Provide ease of deployment and retrieval for purposes of construction and repair

8. Have a lifetime of 3 to 5 years for practical and economic utilization

9. Have a capability of full submersion to avoid ice damage in areas of severe winters

10. Provide for attachment of appropriate instrumentation to measure light, temperature, and stresses upon the structure

11. Be constructed of nontoxic, inexpensive materials which, it is hoped, would also possess antifouling properties

12. Provide mechanisms for alteration of buoyancy characteristics in response to weight variation with plant biomass and biofouling increases

13. Provide a structure which will be of intrinsic interest, thereby stimulating public awareness of the potential for seaweed farming

Not addressed in the workshop, but clearly to be dealt with as macroalgal culture moves ahead, is the setting of priorities for questions and answers. How far do we move in answering fundamental biological questions before addressing the bio-engineering issues? Have we passed the point at which the latter must be addressed for effective substrates to be developed? How then do we back up, and delay biological/physiological/genetic issues, while pursuing more pragmatic values necessary for design purposes? The latter, in the eyes of some reviewers of funding proposals, can be seen as lacking substance.

But as the culture of macroalgae evolves from the culture of one, or several, plants as biological entities to the cultivation of large numbers of plants as a crop, issues of substrate, of protection of crop from damage and loss, of access for harvesting, and a myriad of others will intrude and become a larger part of the agenda. To the extent to which this workshop addressed such issues, it was successful in highlighting directions for the future.

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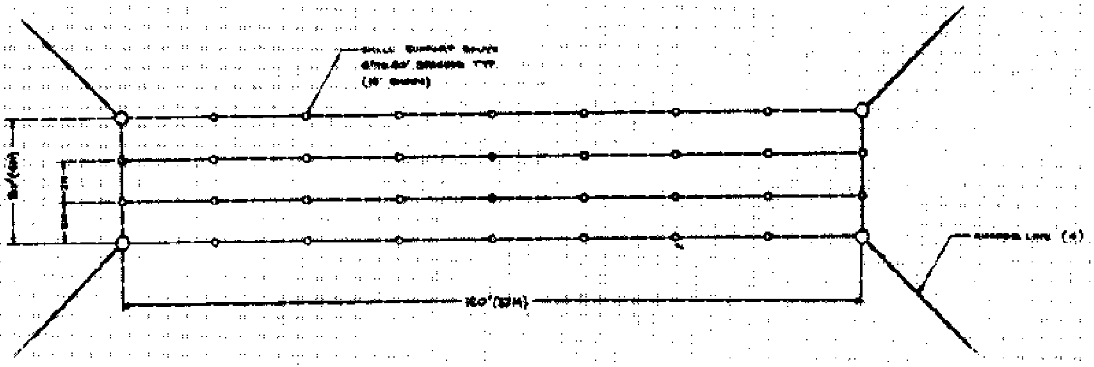

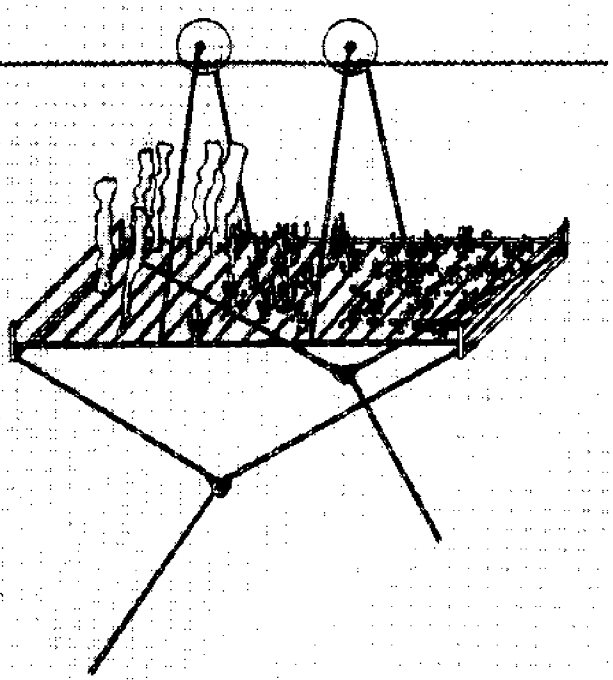

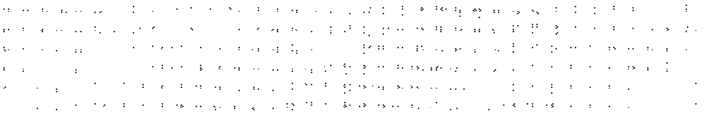

10m max.
2.3m min.
PLAN
A
B
C
SURFACE