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PROCEEDINGS OF A WORKSHOP ON ENVIRONMENTAL IMPACTS OF MARINE BIOMASS

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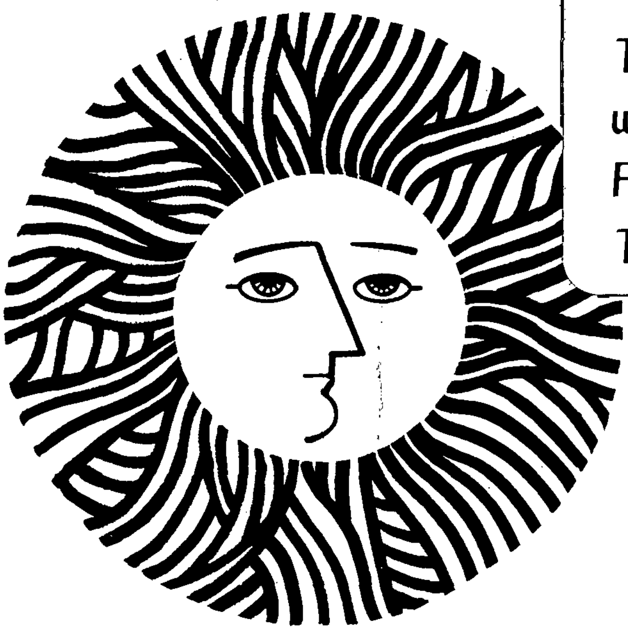

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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PROCEEDINGS OF A WORKSHOP ON

ENVIRONMENTAL IMPACTS OF MARINE BIOMASS

FINAL REPORT

(February 1981 - October 1981)

Prepared by

R. Ritschard, V. Berg, and S. Killeen

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Berkeley, California 94720

For
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A workshop to discuss environmental issues related to marine biomass production was held in Napa, California. The participants included 40 experts from a wide range of marine disciplines including biological, chemical and physical oceanography. The workshop identified and evaluated potential environmental issues of an open ocean biomass system and made research recommendations to GRI for needed environmental studies.

Several critical issues were identified that need to be addressed by the GRI environmental research program. A detailed assessment is needed of the particulate organic matter (POM) flux from the kelp to the deep water column and sediments in order to determine the impact of kelp farming on ocean oxygen budgets, considering kelp fragments and residues from the anaerobic digestion process. Also, it is necessary to understand the dynamics of upwelled water especially related to nutrient availability and uptake. In addition, from an engineering and operations aspect, a critical test farm experiment is required of the farm structure, including its associated pumps (wave-driven) and attachment lines. Finally, the issue of digester residue disposal must be evaluated to suggest environmentally acceptable disposal or utilization practices.

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Research Summary

Title	Proceedings of a Workshop on Environmental Impacts of Marine Biomass Accession Code: GRI-80/0076 GRI Contract Number: 5080-351-0392
Contractor	Lawrence Berkeley Laboratory Energy and Environment Division, University of California
Principal Investigator	R. Ritschard, V. Berg and S. Killeen
Time Span	February - October 1981 Final Report
Major Achievements	A workshop to discuss environmental issues related to marine biomass production was held in Napa, California. The participants included 40 experts from a wide range of marine disciplines including biological, chemical and physical oceanography. The workshop identified and evaluated potential environmental issues of an open ocean biomass system and made research recommendations to GRI for needed environmental studies. Workshop format included two working group sessions (biological and physical/chemical), alternating with plenary sessions to discuss and refine the issues. Two predominant biological issues identified included the effect of sinking organic particles on the oxygen budget and biological fate of upwelled water. Physical/chemical issues discussed were related to farm configuration, the upwelling system and structural integrity with regard to currents, waves, climate, and other hydrodynamic factors.
Recommendations	Several critical issues were identified that need to be addressed by the GRI environmental research program. A detailed assessment is needed of the particulate organic matter (POM) flux from the kelp to the deep water column and sediments in order to determine the impact of kelp farming on oceanic oxygen budgets, considering kelp fragments and residues from the anaerobic digestion process. Also, it is necessary to understand the dynamics of upwelled water especially related to nutrient availability and uptake. In addition, from an engineering and operations aspect, a

critical test farm experiment is required of the farm structure, including its associated pumps (wave driven) and attachment lines. Finally, the issue of digester residues disposal must be evaluated to suggest environmentally acceptable disposal or utilization practices.

Description of Work Completed

This workshop identified and evaluated potential environmental issues of an open ocean biomass farm concept. A series of ranked recommendations for needed environmental research related to marine biomass production was the end result of the workshop. The following issues were examined:

Biological issues were grouped into four major areas: effects of kelp debris, impacts on organisms, effects on biological communities, and biochemical/biophysical issues, such as upwelled water, temperature, climate, etc. The most important biological issues were related to debris from kelp and from the onshore processing facility and the biological effects of upwelled water. Other issues included entrainment of organisms, the effects of an open ocean farm on migrating animals and fisheries, attraction to the farm of new species, temperature changes, and water circulation.

Physical/chemical issues were organized into three broad categories; oceanographic, design, and operational. Physical/chemical issues included the effects of ocean currents, waves and upwelled water on the farm structure and operation. Issues related to the stability and survivability of the farm structure were also identified as were the selection of appropriate sites and farm configuration.

Five areas of research identified by the workshop participants were considered to be of high priority. First, it was suggested that kelp yields from offsore farms should be more precisely defined in order to evaluate the potential environmental impacts. Second, an assessment of the particulate organic matter flux from both offshore farms and onshore conversion systems was needed to determine the impact on oceanic oxygen budgets. Third, a better understanding of the dynamics of upwelled water within the farm could help determine design issues such as pumping rates and siting criteria.

Fourth, acceptable methods for utilizing or disposing of fermentation residues should be identified and evaluated. Fifth, it was suggested that practical site selection criteria be developed and applied that consider site features, farm characteristics and site usage.

GRI COMMENT

GRI agrees with the recommendations set forth in the Marine Biomass Workshop proceedings. The purpose of the workshop was to bring together experts in the marine sciences field to identify and discuss the potential environmental issues of an open ocean biomass system. The discussions from the workshop have successfully led to a report with a series of recommendations for needed environmental research related to marine biomass production. These recommendations, with input from GRI's Supply Division, will be considered in light of program shifts made in GRI's Marine Biomass Program, and will form the basis for environmental research projects in marine biomass in the near future.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

SECTION | Page

LIST OF TABLES

SECTION 1

INTRODUCTION

Lawrence Berkeley Laboratory (LBL), under the sponsorship of the Gas Research Institute (GRI), conducted a workshop on the topic of "Environmental Impacts of Marine Biomass". The workshop was held in Napa, California, on April 7, 8, and 9, 1981 and involved over 40 experts from a wide range of disciplines including biological, chemical, and physical oceanography, ocean engineering, and several related marine areas. Appendix A lists the participants in the meeting.

The workshop had three objectives. First, the participants were asked to identify the potential environmental issues, both positive and negative, of an open ocean biomass system that employs artificial upwelling. Second, the experts evaluated each issue through an extensive discussion to determine how critical the issue was to the success of the marine biomass program. Finally, the attendees developed a set of recommendations for GRI that suggested research needs regarding the environmental aspects of the kelp farm system.

The format of the workshop provided a flexible structure emphasizing small working groups. The first day of the meeting commenced with a presentation of the marine biomass program by the prime contractor, Re-Entry Systems Division of the General Electric Company. This presentation set the boundary conditions for the subsequent working group sessions. The participants were divided into two working groups--biological and physical/chemical--that identified and evaluated the potential environmental issues in their area of expertise. Interaction between the two groups was encouraged through periodic plenary sessions where each chairman and selected participants presented a summary of the working group activities. These meetings of the entire group provided an opportunity for further elaboration and refinement of the specific issues and subsequent research recommendations produced by each study group.

The proceedings are organized into four major sections. The first section, "Marine Biomass Farm Concept," provides a brief history of the marine biomass program and a description of the open ocean kelp farm. The 1000-square mile commercial farm concept is described, as well as the quarter-acre biological test farm currently deployed 4.5 miles off the coast of southern California.

The second section, "Biological Issues and Recommendations", is primarily a summary of the discussions of the biological working group. It includes a description of specific issues from a biological perspective and the areas of recommended future research that appear to be both achievable and necessary for the future success of the program.

The third section, "Physical/Chemical Issues and Recommendations", is the product of the physical/chemical study group. It contains a discussion of the specific issues relevant to the expertise of the group and several research recommendations.

In the final section, "Conclusions", an attempt is made to incorporate the working group findings into a final set of recommendations. Several critical issues were identified by the workshop participants that should be addressed before the marine biomass program proceeds much further.

SECTION 2

MARINE BIOMASS FARM CONCEPT

A marine biomass farm is one of the few biologically-based systems that has the potential to contribute large quantities of synthetic gaseous fuels to the nation's future energy supply. This is especially true because biomass grown in the open ocean would not be limited by space, plant nutrients or water availability as it is on land. In this section, the history of the marine biomass program is briefly outlined and a description of the commercial size farm, which was used as a hypothetical model during the workshop discussions, is provided.

2.1 History of Marine Biomass Program

In 1974, the marine biomass program was initiated by the American Gas Association (AGA) and the Energy Research and Development Administration (ERDA), with the U.S. Naval Undersea Center in San Diego, California, as prime contractor. The overall objective of the program is to develop a system for the production of methane gas on a commercial scale that will contribute in a major way to the nation's gas supply.

In 1976, the prime contract was shifted to the General Electric Company's Re-entry and Environmental Systems Division because G.E. had the capability and corporate interest to develop and commercialize such a system. A year later, AGA's research program was transferred to the Gas Research Institute (GRI) and the Department of Energy (DOE) assumed the activities of ERDA.

The marine biomass program, which has funded over $9 million of directed research since 1974, continues under the joint sponsorship of GRI and DOE. This arrangement is currently being altered. In addition, supporting research projects aimed at a better understanding of marine plants, their cultivation and potential new uses, have been funded by several other Federal agencies to a total of about $1 million a year.

The approach utilizes the concept of growing macroalgae on an open ocean farm to capture and store solar energy through the photosynthetic process. The macroalgae, after harvesting, are then converted by anaerobic digestion to pipeline quality substitute gas--methane--and other possible byproducts (fertilizer, animal feed supplement, chemicals, etc).

2.2 Overview of Commercial Marine Farm

The basic concept of the marine biomass system is to culture and harvest seaweed plants on artificial structures submerged at the same depth as natural kelp beds. Marine kelp require light, carbon dioxide, water, and nutrients from the surface layers of the ocean. However, many of the areas, especially along the southern California coast, that would support marine algae may be nutrient-limited for most of the year because of a lack of upwelling. Therefore, fertilizing operations are clearly necessary to produce high yields of kelp on ocean farms. The selected process for fertilization is to pump up nutrient-rich waters from depths of several hundred to a thousand feet.

Past and present work on this program has had the primary objective of determining the economic and technical feasibility of a system for the production of methane from California giant kelp, Macrocystis pyrifera, grown on man-made structures in the open ocean. Macrocystis was selected as the biomass source because of its high growth rate, its size, structure and growth patterns that allow it to be mechanically harvested, and its year-round growth cycle. Table 1 lists some baseline parameters regarding the composition of Macrocystis.

TABLE 1
MACROCYSTIS PYRIFERA COMPOSITION

KELP COMPOSITION	Water 87% Total Solids 13% Volatile Solids 7.6%
CHEMICAL CONTENT (of volatile solids)	Carbon 30% Nitrogen 1.6% Phosphorus 0.3%
ENERGY CONTENT	8000 Btu/lb. dry ash-free (DAF)

A set of basic parameters for a hypothetical 1000-square mile commercial size farm was presented to the workshop attendees (see Table 2). This size farm, which could theoretically contribute about 0.3 quads of substitute natural gas (SNG) to the nation's current natural gas supply of 22 quads, could represent a commercial scale operation. The specific configuration and other dimensions and properties of the farm should be viewed only as hypothetical values of the baseline system that was used by the participants in their environmental examination. Figure 1 depicts the elements of the hypothetical system. The actual dimensions and parameters are dependent upon cost studies, yield analyses, and other technical research that is currently underway or planned.

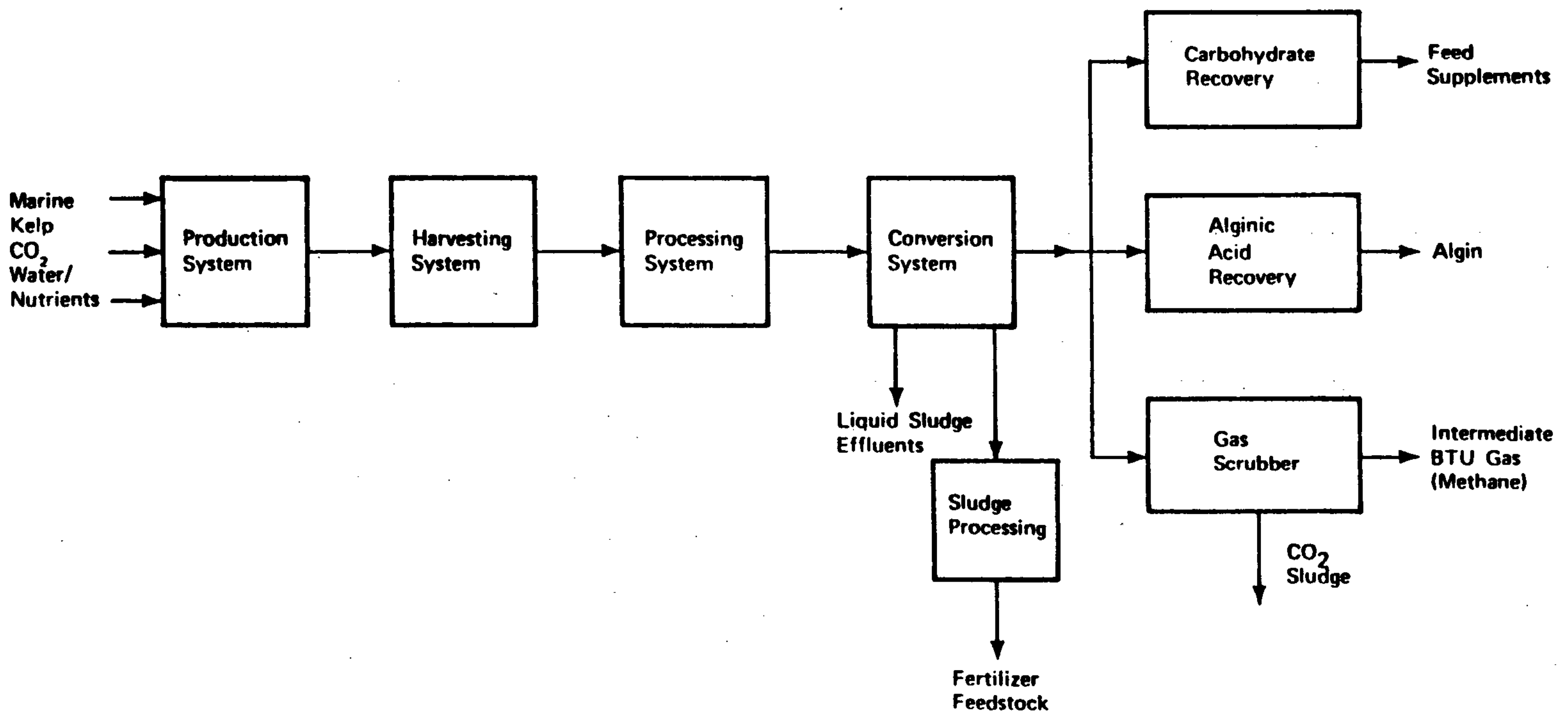

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Figure 1. Complete Marine Biomass System

TABLE 2 BASIC PARAMETERS--COMMERCIAL KELP FARM	
SITE LOCATION	California coastal waters (about 20 miles offshore)
BIOMASS SOURCE	*Macrocystis pyrifera*
BIOMASS REQUIREMENT	279 million kelp plants
PLANT SURVIVAL	20% plant loss per year due to environment and harvesting
YIELD POTENTIAL	50 DAF tons/acre-year (Range: 25-75 DAF tons/acre-year)
NUTRIENT REQUIREMENT	3 microgram atoms Nitrogen/liter
STATION KEEPING METHOD	Bottom moored
UPWELLING SYSTEM	Direct Displacement Wave Pump
UPWELLING REQUIREMENT	2100 gallons/minute/acre
UPWELLING DEPTH	300-1500 feet
CONSTRUCTION MATERIAL REQUIRED	6690 kilotons concrete 760 kilotons steel 3970 kilotons synthetics

In the kelp farm discussed at the workshop, the standing crop is harvested by special ships several times a year. These vessels are patterned after the Kelco Company design used for commercial harvesting along the California coast for many years. Some pre-processing, e.g. removal of water and grinding, could be accomplished on the harvesting ships prior to transporting the kelp to onshore processing plants. This pre-processing step was not included in the system used as a prototype. The only harvesting and transportation information available to the attendees was an estimate that a commercial size farm (1000-square miles) would require as many as fifty 10,000 dwt (dead weight ton) ships making three roundtrips per day to the onshore dock facility and pipeline system.

The SNG processing and conversion plant was hypothetically sited one mile inland from the dock facility. It was assumed that the raw wet kelp would be shredded and subsequently transported by pipeline to the process site. The digester itself would require a unit capacity (inside volume) of about one million standard cubic feet, which is about 2.5 times the largest existing digester. The process would also include a carbon dioxide scrubbing unit, which releases pure carbon dioxide, and compressors for delivery of pipeline quality natural gas.

Several separation steps are usually used to segregate the electrolytes, carbohydrates, water, and volatile solids (VS). The volatile solids (about 60 percent) go into a heated air-tight digester where methane and carbon dioxide are produced. The feedstock is decomposed over a period of about two weeks by bacteria in the absence of oxygen. A waste sludge, high in nitrogen, will also result. Table 3 contains the basic parameters of the digestion process.

TABLE 3
BASIC PARAMETERS--KELP DIGESTION PROCESS

METHANE YIELD	5.5 Standard Cubic Feet (SCF)/lb. volatile solid (VS) added
RETENTION TIME	10-18 days
LOADING RATE	0.2 lb VS/SCF
TEMPERATURE	$35^{o}C$
DIGESTER GAS COMPOSITION	Methane-60% (by volume) Carbon Dioxide-40% (by volume)
PRODUCT GAS OUTPUT	3.48×10^{11} SCF methane/year 2.32×10^{11} SCF carbon dioxide/year
DIGESTER RESIDUE	200 million tons/year

Since there are no full-scale marine farm systems in operation today, the parameters that were used at the workshop represent a compilation of data from bench-scale experiments, from conceptual plans, and from the data obtained on a biological test platform placed 5 miles off the coast in southern California. In order to provide a data base on kelp yield, which is one of the key parameters affecting the initial capital requirements and unit gas costs, GRI and DOE have been designing and constructing nearshore biological test farms. These experimental test facilities are being used to conduct kelp yield experiments on adult kelp plants in a controlled fertilization environment.

The identification of important environmental issues and the recommendations of research to address these issues were developed at the workshop using the design parameters described here. No attempt was made to predict what an actual marine biomass farm might look like. Rather, the information was used to provide sample conditions within which a discussion of potential environmental concerns could be conducted.

SECTION 3

BIOLOGICAL ISSUES AND RECOMMENDATIONS

The development of a commercially viable ocean kelp farm will require that certain biological processes be considered. Most important among these processes is the question of kelp growth, productivity and stability in an open ocean system. The issues and research recommendations listed below are presented at various levels of organization including the effects of kelp farms on other organisms, biological communities and certain biochemical and biophysical activities.

3.1 DEBRIS-ISSUES

3.1.1 Sinking of Organic Particles and the Oxygen Budget

An important issue is the impact of sinking organic particles from the farm on the deep water column and the ocean bottom and their associated biota. The sinking material will have a high biochemical oxygen demand (BOD). If production is 20 dry tons per acre per year, and loss from the farm to a number of causes is 20% of this production, then the sinking flux would be on the order of 2 kg carbon/m^2/yr. This is far higher than normal sedimentation rates and will drive the level of heterotrophic processes beyond the system's capability to renew supplies of oxygen if all this flux reached the bottom. The impact this has on the bottom water column will be a function of circulation and water renewal in the region of fallout.

The area chosen for a biomass farm should not be characterized by subsurface counter currents. If the oxygen (O_2) level is severely reduced, nitrate will then be used as an electron acceptor and the source water for the pumps might be depleted of this nutrient. This should be no problem, in that ammonia (NH_4) can be used as well by kelp plants. Toxicity of NH_4 and reduced sulfur compounds may be a problem, however.

Natural upwelling areas (Peru, Chile, SW Africa, India) with particulate organic matter (POM) sedimentation rates orders of magnitude lower than the estimates for below the farm, as well as areas of restricted circulation (Gulf of California, Cariaco trench, NY Bight, etc.) are characterized by anoxic sediments and often by anoxic deep water. It is reasonable to question how extensive the BOD-loading by the POM losses from the farm will be on the region around the farm.

Regions of anoxic water and sediment will be characterized by an absence of typical biotic communities. All commercial and sports fisheries will be destroyed. Geochemical exchanges between the sediment and water will also be radically altered.

This issue of potential oxygen depletion in the deep water column and bottom sediments, due to a greatly enhanced sinking flux of organic particles from kelp farming, is one of the most serious potential problems that has been identified. The sinking flux will be an order of magnitude greater than in the natural system off southern California. It may be further increased if fermentation residues are returned to the kelp farm for disposal.

3.1.2 Kelp Wrack (drift kelp)

Normal Conditions

Under typical sea conditions there will be a constant shedding of kelp plant fragments from the kelp farm. Those with intact floats will come to the surface; those without floats will sink.

Presumably, there will be a prevailing current direction so that it should be feasible to establish trap-nets down current from the farm and thus catch virtually all floating kelp fragments. It seems likely that the cost of a net entrapment system will more than pay for itself in kelp caught and at the same time eliminate the floating fragments as a nuisance or source of BOD.

Kelp fragments that sink will probably move some distance and become widely dispersed. If this material should be trapped in quantity at various locations on the bottom, it will result in areas of anaerobic conditions.

Storm Conditions

Under severe weather conditions, large quantities of kelp may be torn loose in a short time. Since most of this material will consist of large pieces, most of it will have functional floats and should remain at the surface. If weather conditions are not too severe, most of the kelp may be caught in the retention nets envisaged and thus salvaged. If, however, it drifts ashore, it seems likely that the quantities will be large enough to make it profitable to harvest it from the beach, or, if not actually profitable, the cost of beach cleanup will be largely offset by the value of the product.

In general it appears that kelp lost by fragmentation, if of sufficient quantity to constitute a nuisance, will also be of sufficient quantity to justify recovery in one way or another.

3.1.3 Impacts of Farm Failure and Problems of Waste Disposal

A marine farm of 1000 - square miles will be composed of a standing crop of kelp equal to about 1 million tons wet weight. In addition, such a farm will be constructed of floating and non-floating structural material equal to about a million tons. What is the fate and impact of this material if all or part of this becomes dislodged?

In the simplest case, we can assume that small sections of line, buoys, and kelp will be lost on a more or less continuous basis. In the event of a storm, we assume 10% of the standing kelp stock (100,000 tons) will be lost. Assuming 90% of this goes out to sea or sinks, 10% or 10,000 tons is left to drift onto beaches. If this impinges on 100 miles of coastline, then each foot of beach will receive about 40 pounds of kelp.

A worse case would be what we call the "tumble weed" effect. Imagine a small percentage of farm edge plants break loose and drift with wave force into the farm. The combined weight of these kelp on attached plants may well be enough to break them free and add to the wave-driven drift mass. This process could continue until the entire farm is stripped clean. The immediate consequences would be a million tons of drifting kelp.

In a more severe case, large sections or the entire farm (structure and kelp) could break loose. A serious question then arises as to the fate of this mass: it could float and drift, sink to the bottom (depending on the degree of fouling), or come to rest at some intermediate depth in the water column.

What are the consequences of all these various degrees of failure? In the first case, small pieces of line and buoys could become navigational hazards and would also result in continuous impingement of these pieces onto beaches (unless recovered).

In the more serious, but highly probable, case of storm-induced losses there could be significant sea-coast effects on recreational uses, shoreline pollution, increases in kelp fly populations and problems of disposal.

In the case of combined structural and kelp loss there could be significant and deleterious impacts on the sea-floor and/or coastline along with significant problems of waste disposal. There could also be significant effects on bottom commercial fishing and on commercial and military navigational hazards. A very real problem might be second and third order effects: a drift farm (floating or submerged) could run into oil rigs or block a harbor; a sunken farm, once divested of its biofouling and additional weight, could at some future and possibly unpredictable time resurface to pose new hazards. Environmentally, a 100 square mile farm sitting on the bottom could render 100 square miles of bottom anaerobic (possibly killing all trapped infauna), with eventual degassing of hydrogen sulfide (H_2S) into the water column.

3.1.4 Effects of Biomass (Kelp) Conversion to Methane

This environmental issue is related to the installation and operation of the anaerobic digestion kelp conversion system and the fate of digester residues. Table 4 lists the assumptions that serve as a basis for this discussion.

TABLE 4

BASIC ASSUMPTIONS - KELP CONVERSION

Farm size - 1000 mi^2

Digester Volume - 500 x 10^6 ft^3

Digester Area - 400 acres (several units)

Total Area for conversion plant - 700 acres

Digester loading - 0.2 lb VS/ft^3
- 0.33 lb TS/ft^3 - day
- 2.75 lb wet $kelp/ft^3$

Methane Yield - 5.5 scf/lb VS added

Methane Production - Rate - 1 SCF/ft^3 digester per day

Hydraulic Retention Time - 20 days

Kelp Input - 1.5 x 10^9 lb VS/day

Output - 0.7 x 10^9 lb VS/day
- 187 x 10^6 gal of slurry/day

Factors to be considered with respect to installation and operation of the digesters are land utilization, use of CO_2 and H_2S removed during gas cleanup, and safety aspects related to handling a potentially explosive gas. In addition, some fresh water will be used for restroom, equipment cleaning, etc.

The major potential environmental impacts of the conversion system will be related to the fate of the digester effluent. We considered four options for use of this material.

Post-Treatment

The residues could be dewatered and treated by one of various techniques, e.g., alkaline hydrolysis or enzyme hydrolysis to increase biodegradability. The treated residues would be recycled back to the digesters to increase methane yields. Alternatively, the digester effluent could be spread on land (about 8000 acres), dried to 50% solids or less, collected, and gasified by thermal gasification. The bioconversion wastes could be used to upgrade the thermal process gases. The ash residues from such a scheme should be considered as a fertilizer. This first scheme should be carefully considered, as the increased methane yields result in smaller farm size requirements.

Animal Feed

Use of digester residues as animal feed may present two problems. The organics have already undergone anaerobic digestion and would thus require treatment to render them digestible. The salt content is high and may result in toxicity to animals. The above residues could supply food (at 50% mix) for 30 million cattle.

Fertilizer

Digester effluent may be suitable as a fertilizer on crops or back into the kelp farm. Approximately 13,000 acres/day might be fertilized up to a maximum total loading of 1 lb/ft^2 because of salt buildup.

Ocean Farm Disposal

The major environmental impacts of disposal of residues on the farm would be biochemical oxygen demand (BOD) and turbidity. BOD may result in reduced dissolved oxygen and turbidity may retard light penetration needed for photosynthesis. By farm disposal, most of the inorganic nutrients would be returned to the farm. The availability of returned nitrogen for kelp growth would depend on unknown variables such as microbial activity in the kelp beds. Assuming 50% availability of returned nitrogen to the kelp, upwelling requirements could be reduced by about 30%. As noted earlier, this disposal method carries with it the potential of increasing the sinking flux of organic matter and the oxygen demand for its decomposition in the deep water column and sediments.

3.2 DEBRIS-RECOMMENDATIONS

3.2.1 Kelp Yield

Define more precisely theisely the kelp yield expected from offshore farming for evaluation of potential impacts. Study of the releases of dissolved organic matter, including phenols, during kelp growth and decay is also needed. Kelp yield research is needed primarily to help determine the environmental impact of particulate organic matter flux mentioned below. (High Priority)

3.2.2 Particulate Organic Matter

A detailed assessment is needed of the particulate organic matter (POM) flux from the kelp to the deep water column and sediments in order to determine the impact of kelp farming on oceanic oxygen budgets. Consider: a) kelp wrack, fragmentation, sloughing and storm damage as sources of organic matter; b) the POM flux due to fouling and other organisms associated with the kelp; and c) the additional POM flux that would be associated with disposal of fermentation residues at the farm site. This information can be used with an appropriate physical-chemical model of the deep circulation at specific sites to evaluate the prospects for anoxic conditions. (High Priority)

3.2.3 Sinking of Kelp Fragments

Essentially nothing is known of the sinking behavior of kelp fragments in the ocean. Experiments and observations are needed to better define the fate of drift kelp, kelp fragments, and POM from the fouling community. (Medium Priority)

3.2.4 Potential Farm Failure

Four possible research areas that might be addressed include: 1) studies of how farms might be built to avoid some or all of the above-mentioned effects; 2) studies of how farms might be monitored using modern remote-sensing technology; 3) studies of how actual farms might be handled and recovered by tugs in event of loss and of what effects fouling will have on how farms are handled; and 4) studies of how oil-spill contingency planning might be "adapted" to the marine farm system.

A key area is, of course, the development of farming technology that should include studies focused not only on enhancing plant growth, but also on how to handle drift kelp, dislodged parts of the farm and kelp, and how to monitor the status of a farm. The monitoring system would be invaluable for scheduling harvesting activity and for tracking and pickup in the case of farm loss.

The problems of decommissioning kelp farms might be substantial but if materials-selection studies include the evaluation of biodegradable and/or recyclable materials, this problem might be ameliorated. Research into mitigation and monitoring could be very contributory to the ultimate success of marine bio-energy farming. (Medium Priority)

3.2.5 Disposal of Digester Residues

Develop scenarios for the several options for disposing of or utilizing the fermentation residues. Recommendations for research on each of the disposal options considered are listed below. (High Priority)

Post-Treatment

Digester residues should be evaluated in terms of dewatering characteristics, including examination of techniques to improve dewatering. This should be followed by evaluation of various post-treatment schemes such as acid, alkaline, and enzyme hydrolysis to improve biodegradability. Thermogasification of dewatered residues should also be evaluated. These options would result in higher methane yields.

Animal Feed

Feeding trials on cattle should be conducted on direct and post treated residues.

Fertilizer

The use of residues on test plots as crop fertilizer should be examined. Particular emphasis should be placed on salt buildup in receiving soils.

Ocean Farm Disposal

Digester effluent should be evaluated in detail with respect to its impact on water quality in kelp beds, kelp growth, ecology of the flora and fauna residing in the kelp farm, and potential reduction of upwelling requirements.

By-products

Kelp digester residues should be examined for potential by-products such as potassium, protein, etc.

3.3 ORGANISMS-ISSUES

3.3.1 Entrainment of Aquatic Organisms

The mesopelagic region between 200 and 400 meters depth is referred to as the Deep Scattering Layer (DSL). The DSL is inhabited by numerous small fish, crustaceans and gelatinous plankton. The organisms of the DSL, along with other pelagic forms, will be subjected to entrainment into a kelp farm's upwelling system. Intake velocities of around one meter/second will preclude many organisms from resisting entrainment by their own swimming behavior. Mortality rates associated with entrainment are unknown, but may be high due to pressure drop, temperature rise and mechanical insult, as well as subsequent predation at the ocean surface. A 25,600 hectare (ha). farm (about 64,000 acres) would upwell approximately 8,000 m^3 of deep water per second, the equivalent water flow of over 100 once-through 1000 MW(e) nuclear plants. Effects of entrainment losses to the local mesopelagic community could well be significant.

Caveats

The upwelled water volume necessary to sustain adequate growth varies directly with kelp yield and inversely with nutrient concentrations at depth and kelp uptake efficiency. Variations from the assumed values for these parameters would correspondingly modify the potential entrainment problem. Entrainment impacts may also be site-specific.

3.3.2 Kelp Farms as Barriers for Migrating Organisms

The majority of species of planktonic, pelagic, neritic, or flying organisms may be expected to float, swim through, or fly over kelp farms. Proliferation of suspension-feeding organisms or predation by fishes living in the kelp farm may be expected to reduce the abundance of offshore planktonic species and their eggs and larvae as well as some fishes, such as anchovy. "Open-water" fishes may be forced to detour around the farms or through channels that are acceptable to them. Concern exists for very large animals, such as whales and basking sharks, that may swim under the network of a floating farm. These animals may attempt to rise to the surface to breathe or to feed, only to find themselves trapped or tangled. Disruption of natural physical or chemical patterns (plume effect), which are important to species of migratory fishes, remain to be evaluated.

3.4 ORGANISMS-RECOMMENDATIONS

3.4.1 Entrainment

Define more precisely the range of parameters related to the amount of upwelled water needed to sustain adequate kelp growth. From this range, investigate the potential for entrainment of several pelagic species. (Low Priority)

3.4.2 Coexistence with Whales

The scale of envisioned farms and grid spacings (10 ft. x 10 ft.) could result in large (probably rare or endangered) cetaceans becoming entangled and dying when attempting to breach the surface for air.

If farms will ever be sited in or along cetacean migration routes, then farm design criteria should include features that will allow them reasonable passage through the structure.

Potential solutions include: changing the grid spacing; moving from grids to parallel substrate lines; a system of "ice hole" channels; and contingency plans for rescue of entrapped animals. (Low Priority)

3.5 COMMUNITIES-ISSUES

3.5.1 Kelp Farms as Sites to which Marine Organisms will be Attracted

Kelp farms will serve as suitable sites for attachment by or attraction of many benthic, pelagic, or neritic species adapted to the continental borderland of southern California. Many of these species will find habitat for feeding, reproduction, or resting (especially birds).

This effect may be as beneficial to the abundance and survival of these organisms. A portion of the species, which prosper in this situation, may become pests, as fouling organisms contributing to weight and drag, or grazers on kelp, e.g., isopods, urchins, and some fish. Some organisms will find the farms to be unnatural substrates. This may result in the loss of those bottom dwelling (benthic or demersal) species that recruit from the plankton into kelp beds or onto structures as juveniles and then migrate to the bottom to mature. Included among such species are crabs, lobsters, some rockfishes, and the damselfishes. These species may be unable to migrate from the kelp farm to suitable habitat on the mainland or the Channel Islands. Mid-water organisms may rise in the shadow of the farm during the day or fail to descend after rising at night, thus disrupting the natural pattern of their vertical distribution. Mid-water organisms in the shadow of the farm may be entrained by the upwelling pumps. This could result in the introduction of "food" in the surface waters of the plume of discharged (upwelled) water that will lure other organisms into the kelp canopy.

3.5.2 Ecosystem Alteration

Construction of a large offshore kelp farm would unavoidably displace portions of the natural ecosystem in the area, replacing it with an ecosystem based around the kelp farm structure. Some of the species displaced include deep sea fin fish, plankton, certain pelagic birds, and possibly benthic organisms. Species introduced include kelp, nearshore fish species, and species living on a substrate, such as sea urchins, abalone, starfish, limpets, etc. Any substrate-dwelling organism that is displaced would sink to the bottom and die, in contrast to the situation in a natural kelp bed in shallow water. This form of density-independent mortality may alter the population dynamics of these species.

Sea otters would probably be able to migrate thirty miles offshore to a kelp farm. Since they do not need to leave the water to give birth, a self-sustaining population of otters could become established.

The pelagic ecosystem of the southern California Bight has a mean primary production rate of about 0.4 grams carbon/square meter/day. Production rate of a kelp farm is expected to be an order of magnitude greater. Animals depend on phytoplankton, and in fact, the natural pelagic food web may be essentially displaced by large kelp farms, depending upon the way sunlight is shared between kelp and phytoplankton. Phytoplankton production within existing kelp beds has not, as far as we know, been evaluated and compared with that in similar kelp-free sites.

3.5.3 Value-Related Issues: Bio-Resource Management Techniques

A large kelp farm operation may engender controversy over the highest and best use of ocean resources. The debate would result from differing value judgements on the part of individuals about the relative merit of ocean uses. Open-ocean areas have always been natural, variable and diverse. Conversion to an artificially established and maintained monoculture would be the result of a declared or implicit decision as to the relative value of natural and modified ecosystems.

Based on present technology, propagation and fertilization techniques would require frequent and large-scale human intervention and an intensive artificial management process rather than natural processes. It is anticipated that significant improvements in this area will be possible through an increased understanding and manipulation of the genetics and life cycles of the plants. Another approach would be the use of less intensive management techniques such as natural recruitment of kelp, nitrogen fixation instead of artificial upwelling, and natural control of grazers which may make the kelp ranch concept more desirable to members of the public and more feasible in execution.

Thought should be given to the ecosystems and human activities displaced by large scale kelp farming. The extensive structure required for kelp farming essentially precludes other uses. Passage of large vessels, deployment of commercial fishing gear and similar activities are precluded by the structure of the kelp farm, as discussed more fully in the report of the physical-chemical working group.

As noted earlier, the plankton and larger organisms dependent upon them may be essentially displaced, depending upon the distribution of light and nutrient resources between kelp and phytoplankton. Even benthic organisms with widely dispersed planktonic larvae, and fishes whose larvae depend upon planktonic food webs, i.e., essentially all pelagic species, may be adversely affected.

3.5.4 Weed species

Large offshore structures may increase the spread of undesirable species between coastal environments. A species that normally cannot survive a passage between two areas may make it to the farm and survive as a colonist. New generations can then spread from the farm into unaffected areas. In the past, several seaweeds such as Sargassum and Codium have been accidentally spread by man's activities and have caused economic and ecological damage.

3.6 COMMUNITIES-RECOMMENDATIONS

3.6.1 Relationship of Kelp Farm to Fisheries

Creation of a large, about 1000 square mile, kelp farm on the continental borderland of southern California may be expected to impact both sport and commercial fisheries in at least three ways: 1) traditional pelagic fisheries e.g., tuna, swordfish, jack mackerel, etc. will be replaced by the kelp farm; 2) fisheries for species attracted to kelp or floating objects will be enhanced, e.g., yellowtail, barracuda, etc.; and 3) specific proprietary commercial fisheries may be developed on the farm itself (polyculture). Each fishery must be considered in environmental, institutional, and socioeconomic contexts, following applicable legal and policy directives with the objectives of: a) minimizing conflicts between user groups; b) maintaining balanced indigenous populations; and c) providing an acceptable financial environment in which the project may proceed. (Medium Priority)

3.6.2 Community Identification and Relationships

Define more fully the biological communities, both benthic and pelagic, expected to be associated with large offshore farms. Consider the impact of these assemblages on the carbon and oxygen budget and on "pest" control aspects. Is there also a relationship between these assemblages and harvestable fish? (Medium Priority)

3.7 BIOCHEMICAL/BIOPHYSICAL-ISSUES

3.7.1 Fouling on Structures

Fouling on the farm structure by barnacles, mussels, oysters, bryozoa, hydroids, algae, and other organisms would be extensive and would be a constant source of organic matter falling to the bottom. Decomposition there would release nutrients and deplete dissolved oxygen levels.

An advantage to this fouling is that among the components would be bluegreen algae that fix nitrogen. These might be a significant source of fixed nitrogen to the kelp farm.

3.7.2 Non-Natural Chemicals and Wastes

Even if strict precautions are taken, some releases of harmful chemicals and wastes can be expected from an operation of the size contemplated, ie. 100 to 1000 square miles. Depending on the synthetic polymers used for algal supports, a variety of organic chemicals may be leached into the water. These include 1) plasticizers used to make the line pliable, 2) unreacted monomers and lubricants left over from the manufacturing process, and 3) breakdown products from deterioration of the line (for example, when nylon breaks down in sea water it releases aldehydes). In addition, there are environmental hazards associated with the toxic metals used in antifouling paints and wastes generated on the farm platforms (lubricating oil, human wastes). Accidents involving the harvesting boats may also release unwanted organic chemicals (diesel oil, etc.) into the water. Finally, chemical pest control agents may become an important problem. The large scale monoculture of plants on land is usually possible only with the use of chemicals for pest control, and a similar problem can be expected in the algal monoculture planned. However, since the farm structure and operation must be completely compatible with kelp growth and conversion, it is expected that the problem of releasing toxic materials will be continually addressed throughout all phases of research.

3.7.3 Organic Exudates

Dissolved organic compounds are released by algae into the water during the course of photosynthesis. In some kelps these are produced at rates as high as 40% of the total carbon fixed, although values as low as 1% are more typical. Most of the exudates are low molecular weight sugars, which are readily degraded by bacteria, but in certain kelps up to 1% of the total carbon fixed is released in the form of toxic tri-hydroxy-phenols.

3.7.4 Weather and Climate: Biological Effects

Natural upwelling areas tend to be foggy and adjacent land areas tend to be arid. Enhanced offshore upwelling associated with large-scale kelp farming would be expected to enhance these effects, if the area farmed were sufficiently large. This and many other potential environmental issues are a function of the scale of operations. These effects are expected to be small and probably insignificant.

Reduction of insolation due to fog can be expected to reduce photosynthesis within the kelp farm, as well as plankton production in affected areas. These effects are expected to be small.

3.7.5 Habitat Alteration Within the Kelp Bed

Biological alterations

A large bird population is likely to be attracted to the farm and will input their excretion products to the surface waters, as well as feed on organisms associated with the kelp bed. The bed will provide food for some fish populations and increase their productivity. The kelp farm will also provide a habitat for a large number of invertebrate species. The plankton population in and around the bed may be increased due to nutrient upwelling, depending on light availability.

Physical-chemical alterations

Increased heterotrophic respiration will increase oxygen demand inside the farm. The nutrient regime and water density structure will also be altered. Some or all of these changes may be transported outside the farm by water movements.

3.7.6 Habitat Alteration in the Water Column Below and Downstream of the Farm

The presence of the farm at the surface will disrupt normal vertical distribution patterns of the mid-water pelagic community. To the extent that portions of this community depend on feeding at the surface, the farm may have detrimental effects on this community. The export of dissolved and particulate material from the farm will affect the water column below and downstream of the farm.

Dissolved material

The physical-chemical characteristics of the surface water will be changed as a result of mixing with deep water, and as a result of the metabolic activity of the kelp and the associated flora and fauna. This may affect the composition of plankton communities in the downstream "plume." These changes, if they occur, may in turn affect other trophic levels that feed on these plankton.

Particulate material

Small detrital particles from the farm will undergo degradation in the water column and possibly change the physical-chemical characteristics of the water column by, for example, increasing O_2 demand. The detritus will also attract organisms that feed on such particles, and is likely to change the abundance and/or composition of this mid-water community.

3.7.7 Biological Fates of Upwelled Water

The nutrient-rich deep water brought up to fertilize the kelp plants will be colder and saltier, and hence of greater density than the surface waters. It will tend to sink, mixing with surface water in the process. Ideally, the kelp plants will deplete this water of its plant nutrients, such as nitrate, phosphate and certain trace metals. Certain other nutrients, such as silicate, are present in the upwelled water but are not required by kelp plants, and may not be taken up by them. Such substances may serve as tracers to aid in identifying the motions of this water, along with temperature and salinity.

Many trace metals as well as nutrients increase in concentration with depth in the ocean. Depth profiles of their concentration vary with the element in question, such that ratios of one element to another also change with depth. The upwelling of deep water, natural or brought about by man, thus brings to the ocean surface not only higher concentrations of nutrients and trace metals, but also changes their relative proportions. Chemical oceanography has shown that certain trace metals, such as copper, are present in deep water at concentrations sufficient to inhibit the growth of certain species of phytoplankton. It is the free cupric ion, rather than chelated or otherwise complexed forms of copper which is responsible for the toxicity. Upwelling of deep water on a massive scale is thus of some concern due to the potential for toxic or growth inhibiting effects of copper or other trace metals on surface-living plankton.

3.7.8 Biological Effects Resulting from Alteration in the Circulation

A large offshore kelp farm can be expected to modify the character of surface ocean currents as well as wave spectra. The extent of such changes in circulation are not clear and will depend on the physical characteristics, size and shape of the farm as well as local circulation regime. Several features inshore of the farm can be expected to change, such as the local sediment transport, larval drift, and vertical features of plankton distribution. These effects would result from internal water motions of the density and nutrient fields.

3.7.9 Temperature and Biological Activity

The upwelling of cold, deep water required to provide nutrients for kelp growth will result in a lowering of temperature of surface waters. The magnitude of temperature decrease is anticipated to be the order of 5°C, depending on the scale of operations. Biological rate processes generally decrease about two-fold with a ten degree (celsius) decline in temperature. Surface-dwelling organisms incapable of regulating their body temperature would be slowed in their metabolic activities, but the effect of this on the structure of pelagic marine communities is not clear. Long-term, steady state lowering of sea surface temperatures may result in species shifts analogous to differences in community structure observed naturally as a function of latitude. Certainly the pelagic community associated with a kelp farm will change from its natural state but it is not clear how simultaneous changes in ambient light, temperature, and water chemistry (along with a fundamental change in primary producers, from phytoplankton to kelp plants) will interact to alter the assemblages of pelagic animals. The habitat may be altered to a degree not yet observed in any natural experiment. On the other hand, these temperature changes may not be significant, since surface fluctuations may be greater.

3.7.10 Submarine Light Environment of a Kelp Farm

An open ocean kelp farm, 100-square miles or greater in size, will attenuate light rapidly, removing about 99% of the incident quanta within 10-30 meters of the surface. Most of the light (~90-95%) would be absorbed within 1-2 meters as a result of the dense surface canopy formed by kelp blades. This effect should be largely restricted to light intensity, although wavelength shifts can also be anticipated. Significant changes in the light field are likely to influence marine organisms in manifold ways. The compensation depth (where photosynthesis and dark respiration rates are equal) will occur at a much shallower depth than otherwise. Plankton productivity will thus be confined to depths 3-4 fold less than would otherwise be the case. Phototactic responses of vertically migrating animals will be affected similarly, although these may be even more dramatic due to the more rapid attenuation of those wavelengths absorbed by carotenoid eye pigments. It is possible that this could cause local changes in the depth of the deep scattering layer as well as changes in vertical migration patterns of organisms that cue their activities to ambient light.

In many respects, the construction and operation of a large offshore kelp farm will constitute a unique experiment, somewhat analogous to partially darkening a broad expanse of ocean, previously observed only during solar eclipses. The migratory behavior of mesopelagic animals will surely be affected and the planktonic habitat greatly altered, depending upon the density of the kelp canopy.

3.8 BIOCHEMICAL/BIOPHYSICAL-RECOMMENDATIONS

3.8.1 Pest Control

It is prudent to consider the possible future impacts of chemical treatments that might be employed to control weed species, animal grazers and perhaps even fouling. In Japan, unwanted green algae are selectively weeded from planting nets by treatment with acid. Lime is used in the U.S. to kill grazing sea urchins, and large-scale fertilizer application from fertilizer boats is current practice in China. These and other chemical control methods are almost certainly going to be used in the future.

A test farm, when developed, should include facilities for trial planting where both the efficacy and effects of chemical control can be systematically tested. (Medium Priority)

3.8.2 Polyculture

Consider ways in which polyculture, i.e., the intentional culture of organisms with the kelp, could mitigate or modify issues identified, such as particulate organic matter disposal, non-natural chemicals and wastes, or organic exudates. (Low Priority)

3.8.3 Problems of Scale in Predicting Impacts

Several potential environmental impacts of offshore kelp farming are functions of scale and location. Existing nearshore beds may not be appropriate models for the offshore farms in several respects. Two issues stand out as research needs not amenable to study until offshore farms are functional:

Detrital Food Webs

The planktonic system adjacent to and "downstream" of kelp farms may be influenced by "plumes" of upwelled water, lateral advection of particulate organic matter with enhancement of detrital (POM, bacteria, protozoa) food webs. Although such effects are not likely to be undesirable, we need to know the magnitude of change for full evaluation of the issue. (Medium Priority)

Displacement of Planktonic Communities

Determine to what extent kelp farming will displace the planktonic assemblage and the related natural food web leading to fish. Define how the limiting resources, light and nutrients, will be shared between kelp and the natural plankton assemblages. Determine if the natural planktonic ecosystem will be maintained within large offshore farms. Include in the analysis whether the new communities, which displace natural communities, will be beneficial or harmful. (Medium Priority)

SECTION 4

PHYSICAL/CHEMICAL ISSUES AND RECOMMENDATIONS

Many, if not all, issues related to the impact of the ocean on the kelp farm and to the impact of the kelp farm on the ocean cannot be addressed without understanding physical oceanographic processes. Hydrodynamic loading analyses require input regarding "average" and extreme physical conditions. Offshore environmental impact assessments rely heavily on the transport characteristics (vertically and in plane) of the ocean water.

Consideration of physical oceanographic processes important to the evaluation of issues associated with kelp farms may be conceptually separated into two categories: "natural" processes or processes basically unrelated to the presence of the farm and "farm-induced" or "farm-modified" processes. For example, the "natural" circulation and vertical density structure offshore southern California are important ingredients with respect to several siting issues. Other issues related to both the operation of the farm and the impact of the farm require consideration of the presence and upwelling characteristics of the farm.

Several scales (both spatial and temporal) of physical processes need to be addressed. Spatial scales range from those of several farm "diameters" and deep basin lengths to meters over the mixed layer. Time scales range from basin residence times and seasonal variations to transit times of water through the farm on the order of hours or less. Our attempt here is to deal with only those processes (and related data) and scale considerations important for the kelp farm issues.

Appendix B contains background information that describes the basic physical oceanographic processes offshore from the southern California region.

4.1 OCEANOGRAPHIC-ISSUES

4.1.1 Circulation Patterns and Offshore Kelp Farms

Offshore general circulation supplies oxygen and nutrients to the southern California Bight. It also transports materials, and provides a portion (although a weak one) of the drag forces, which the farm must sustain. Before a farm is built, a more complete knowledge of the deep circulation patterns must be obtained. Large scale water circulation patterns determine the fate of material produced and released by the kelp farm, the replenishment rate of nutrients to the upwelling pumps, and the extent of anoxia in and around local basins.

The southern California Bight is inshore of the California current and is not directly affected by it. Circulation within the Bight is complicated by the subsurface mountain-basin topography extending out 200 kilometers or more. This terrain places constraints on water motion that increase with depth. Deeper water can be exchanged only to the south.

Surface and near-surface features, which occur occasionally in the Bight, include the southern California eddy, (a counter-clockwise eddy located around Santa Catalina Island), and the Davidson Current, (a normally-subsurface weak current from the south). Much information on surface flows has been developed as part of the CALCOFI program. Information is lacking on circulation patterns for depth greater than 200m. Some information exists on exchange rates for basins.

4.1.2 Variable and Medium Scale Currents and Offshore Farms

Variable and medium scale currents are the dispersing agent for nutrients put in the water. They are also responsible for the main part of the drag forces, which the farm as a whole must withstand. Since drag forces are of critical importance for the design of the offshore farm, an extensive and improved knowledge of special scales and the intensity of these currents is imperative.

4.1.3 Small Scale Oceanic Features

The density structure of the southern California Bight waters is characterized by a thin upper mixed layer typical mean value of 60 feet, deepening in winter, and coming closer to the surface in summer. As explained in Appendix B, the waters, which make up the thermocline region, may have northern and southern origins: respectively cold fresh and hot salty. The intermixing of these water types gives rise to large variations of thermal structure in the vertical below the mixed layer. The temporal scale of these variations is not known, but seems to be as rapid as daily and hourly shifts as streams of one or the other move past in an eddying fashion. The importance of the thermocline phenomenon may be low and much data are available in the form of CTD (Conductivity-Temperature-Density) profiles to evaluate its prevalence. The importance of the depth of the surface mixed layer is very high because the farm upwelled water will probably sink to the base of the mixed layer (and modify it).

4.1.4 Fate and Motion of the Upwelled Water Within the Kelp Farm

Importance of Issue

The physical distribution of the nutrients in the upwelled water throughout the upper portion of the water column (specifically, where are the nutrients located and in what concentration?) is essential for estimating biomass production. The behavior of the upwelled water and its interaction with surface waters is discussed here from two perspectives: first in terms of averaged conditions within the mixed layer (assuming no variations within the mixed layer over the entire farm), and second in terms of a more detailed look both vertically and horizontally within the mixed layer.

Simple Box Model for Mixed Layer

If one considers the mixed layer above a square farm of fixed area and fixed mixed layer depth, the flux of ambient surface water into the box from one side and flux of upwelled water up through the bottom dictate the flux of the mixture out the downstream side of the box. The incoming waters are assumed to be well-mixed in the box, and the dilution of upwelled water is readily apparent as follows:

1) The potential dilution of upwelled waters with surface waters increases as ambient currents increase. For example, for the baseline 100-square mile farm and a 20m mixed layer depth, surface currents of 0.1 m/s give volume dilutions of about 3.8 and currents of 1.0 m/s give volume dilutions of about 38. Clearly increased currents mean decreased average nutrient concentrations and less of a temperature reduction in the surface waters.

2) The potential dilution of upwelled waters with surface waters increases with increases in the mixed layer depth (with the same effects as current increases).

3) It is interesting to note, in terms of scale effects, that, for constant current and mixed layer depths, increases in farm area result in potential dilution increases only to the 1/2 power of the area, e.g., an increase in area from 100 to 1000 square miles increases the dilution by $10^{1/2} \cong 3$ times.

The simple box model approach, however, does not reveal anything about the vertical location of the upwelled water (and nutrients) with respect to the kelp, or about the horizontal variability of the nutrient distribution.

Detailed Look Inside the Mixed Layer

The motion of the upwelled water within the mixed layer is more complex than the box model might indicate. Consider first the case of a steady, unidirectional current acting on the farm and the first pumping module (10 acres for the baseline design) in from the upstream edge of the farm.

1) A view in the side of this module indicates that the upwelled water leaves the pump discharge near the surface and sinks (due to negative buoyancy), entraining surface water, to near the bottom of the mixed layer. The specific trajectory of the plume and its degree of dilution depend on the depth of the mixed layer, the density difference between the upwelled and surface waters, the current, and the discharge configuration.

2) When the plume reaches the bottom of the mixed layer and loses its jet-like character, it will collapse vertically and spread horizontally in a relatively thin layer (perhaps a meter or less in height).

As one shifts the view from the most upstream module and looks downstream, the process is similar but more complicated. The intruding plume(s) from the upstream pump(s) slide in along the bottom of the mixed layer building thicker layers and, perhaps, resulting in reentrainment of diluted upwelled water into the plume sinking downward. As one moves further downstream through the farm, the layers built upward into the mixed layer until (depending on the mixed layer depth and the magnitude of the current providing dilution water), the mixed layer is filled with diluted upwelled water. The average temperature in the mixed layer decreases downstream and the average nutrient concentration (neglecting uptake by the kelp) increases to values perhaps near those predicted on the downstream face of the box model. The exact downstream profile of nutrient concentration cannot be determined without modeling. Vertical mixing within the mixed layer due to wind, waves, and kelp motions may destabilize the density stratification enough to modify the distribution.

Of course, the rotation of current direction will switch the downstream nutrient profile axis throughout the farm and may, depending on the time scales for direction changes, result in exposure of all parts of the farm eventually to the largest nutrient concentrations. However, the knowledge of the distribution throughout the farm is necessary to determine the adequacy of upwelling nutrient loading on average.

4.1.5 Effects of Kelp Farm on the Water Circulation and Temperature Distribution

The commercial-size (1,000 square miles) kelp farm may have profound effects on the local circulation and water mass, due to the addition of a large volume of cold deep-ocean water into the upper mixed layer. (In contrast, the OTEC power park, while having a larger discharge rate at each plant, adds a relatively small amount of the water into the upper ocean.) The temperature deficit in the upper layer resulting from the mixing of cold deep-ocean water with the warm surface water, depends on the residence time of the upwelled water. For example, for a mean ambient ocean current of 10 cm/s, a temperature contrast of 13°C, and a mixed layer depth of 20 m, the temperature deficit is about 5°C. This rather large temperature decrease in the upper layer will cause vigorous convective mixing, eventually leading to the deepening of the mixed layer. Entrainment of water from directly below the surface mixed layer may dilute the nutrient concentration, causing perhaps the decrease of plant uptake efficiency. Also, forming a cold pool in the kelp farm may affect the local wind pattern and the water circulation, the latter is associated with the sharp temperature front separating the cold pool from the ambient water. However, it should be noted that the formation of a sizable cold pool depends critically on the assumption of a steady, weak ambient current. The surface current can easily reach a speed of 50 cm/s due to the wind-driven inertial motion and the migrating eddies.

Reliable estimates of the residence time of upwelled water, taking into consideration the transient current, are needed in order to make a more definite statement of the possible environmental impact.

In addition to the possible modification of water circulation by the change in density structure, the kelp farm will dissipate some of the kinetic energy of the current passing through it. There is evidence of dissipation of internal tides by the natural kelp bed in the coastal zone. The effect of a large kelp farm on the ocean current is not immediately clear, but a gross estimate can be made. Withdrawal of deep ocean water in large quantities may modify the nutrient and temperature distribution. The effect can be large because the deep currents are generally weak and hence the residence time is relatively long. The impact probably can be minimized by withdrawing water over a large water column (100-200m) in the less stratified region.

Existing data on the upper ocean current in the California Bight is very limited. On the other hand, there is abundant historical hydrographic data that may be used to derive the spatial and temporal variability of the eddy field. Also, based on studies done in many other areas, the wind-driven inertial current in the upper ocean is reasonably well understood.

4.1.6 Submarine Basin Anoxia Caused by Increased BOD Loading

Basin sill depths ($\geq$ 750m) will preclude an impact on the farm operation, however, the oceanographic impact could be lower oxygen levels in subsurface waters throughout the region.

Water in southern California borderlands has an oxygen minimum at about 600 m. Basins, such as Santa Monica and San Pedro, receive inputs of new water at depths near the oxygen minimum layer. Present high oxygen demand lowers oxygen concentration from about 0.4 ml/l to 0.1 ml/l and nitrate concentration by about 10 micrometers (μM). Increased oxidant demand caused by settling of plant fragments could eliminate oxygen in basins and, possibly, higher up in water column and increase denitrification. Models have been developed to predict the effect of sewage sludge in similar circumstances. These could be applied to the kelp farm situation.

The rates and distribution of settling plant fragments that would stimulate anoxic conditions is unknown as is information on the currents, which distribute anoxic water into other areas. Anoxic conditions could be lethal animals present in basins and animals may be attracted to oxygen fields outside of these basins.

4.1.7 Structural Impact on Wave Climate

The farm acts as a floating breakwater in which waves are dampened but currents pass through relatively unchanged in magnitude and duration. The question then is what are the effects of a dampened wave field on local wave climate and ultimately on inshore habitats.

The amount of effected shoreline is directly proportional to the ratio of farm diameter and distance offshore. It is assumed, as a conservative number, that wave shadows (diffraction of waves around the farm) have no real effect if the distance downstream is on the order of five times the farm's diameter. Thus, for a farm with a diameter or width of one mile, and located five miles offshore, the wave field would essentially return to its previous spectrum and thus, have no effects on inshore processes. As the size of the farm grows, it is important to locate the farm further offshore to minimize diffraction effects.

Since the southern California wave field is generated by an extremely large (virtually infinite fetch namely the Pacific Ocean) there is very little chance of regeneration of the wave field shoreside of a farm. Fetches of 25 to 100 miles can produce wave field with sizable spectra energies, however, it is unlikely that such events would occur near a farm site. The reason is that the wind field is not significantly greater near the southern California shore than in the open ocean. The wind-driven forcing function does not exist shoreside of the farms to generate sizable wave fields once the farms have dampened out the wave energy. Thus for farms that are on the order of hundreds of miles in width and located less than a hundred miles offshore, there will be a very strong potential for nearshore processes to be affected due to the change in wave climates.

Information is available on the mechanics of wave fields from long wind fetches (wind-generated wave mechanics), and on the theories of wave diffraction around objects such as islands or the kelp farm. Although, the degree to which waves are attenuated as they pass through the kelp farm is not known. Global and regional indications of wind fields have been identified that generate the open ocean wave field and the near shore (vicinity of the southern California coast to within 100 miles) wind field. However, data are needed on the details of changes to wave-generated shore processes: such items as shoreline erosion and sedimentation, biological effects of reduced wave forcing and flushing, nutrient transport processes as affected by reduced wave fields, and changes to air/sea interaction in a reduced wave field.

A kelp farm could potentially cause significant changes to the morphology and biology of the California coastline. Essentially, if the wave field is dampened out on the shoreline, a wave action area similar to the east coast would be formulated. Migrating habits could be affected, shoreline structural changes would occur and intertidal biology would be altered.

4.1.8 Climatic Impacts from Large Scale Upwelling

Meso and Global Scale

Additional CO_2 loading of the atmosphere by exchange from upwelled water could potentially occur. However, evidence from recent simultaneous measurements of pH and nutrients in areas of natural upwelling suggests that the bicarbonate increment in upwelled water (in relation to ambient surface water) is removed by the induced phytoplankton growth leaving no excess for net CO_2 outflow into the atmosphere.

Cold surface water presented to the atmosphere could potentially alter climate. Based on recent general circulation model test results, it has been inferred that the surface ΔT presented by several hundred 1000 square mile ocean farms located together in especially sensitive areas, e.g., the N.W. Indian Ocean, which provides the moisture for the Indian monsoons, would begin to exert significant downstream climatic effects.

The above information indicates that only when artificial upwelling is associated with a few degree C surface temperature anomaly covering at least 250,000 square miles will the farm operation have the potential to cause meso- or global-scale climate changes. The 1000-square mile farm is two orders of magnitude too small to cause such changes.

Local Scale

The local climatic effects are relatively undefined, particularly concerning possible interference with farm insulation and productivity. The definition must await realistic hydrodynamic modelling of the farm in its steady state upwelling condition. The key parameter needed for calculating local climatic effect is the mean surface temperature anomaly created by the upwelling.

4.2 OCEANOGRAPHIC-RECOMMENDATIONS

4.2.1 Mean Circulation

Obtain an awareness of existing CALCOFI "geostrophic" data (charts of dynamic topography) in southern California Bight to gain a more complete knowledge of deep circulation. (Low priority)

4.2.2 Variable and Medium Scale Currents

Collect data from current meters, and CTD (Conductivity, Temperature, Density) traces in the southern California Bight. Analyze to determine critical locations where currents should be measured. Install a small number of buoyed and/or bottom mounted current meters and maintain for life of project to gain information of probability distribution of intensive currents. (Medium priority)

If farm is to be built, i.e., after critical experiments have been performed, an extensive current meter study of proposed site should be conducted produce to investigate spatial scale and intensity distribution and to enable detailed farm structural design. (High priority at that time)

4.2.3 Small Scale Oceanic Structures

Existing data, especially CTD profiles from the southern California Bight should be collected and analyzed to provide a probability distribution of mixed layer depths on a seasonal and locational basis. In addition, existing data should be analyzed for stability in the thermocline. (High priority)

4.2.4 Upwelling Dynamics

Develop a model for the fate of upwelled water within the farm based on the present understanding of buoyant jet and plume spreading models and of vertical mixing. Apply the model using a range of representative site and farm design conditions (currents, density structure, pumping rates, substrate locations) to investigate the nutrient distribution throughout the farm and the response of the distribution to temporal changes in ocean conditions. (High priority)

4.2.5 Upwelling and Thermal Structure

A key issue is to determine the residence time of the upwelled water for a commercial-size kelp farm. A first-order estimate can be obtained from numerical modeling of the thermal structure in an idealized kelp farm under the influences of the climatological wind and density (eddy) field. The degree of complexity of model formulation can vary from a simple one-dimensional mixed-layer model with the horizontal temperature flux given, to a fully verified three-dimensional dynamic model. (High priority)

4.2.6 Basin Anoxia

Develop an experimental program to determine circulation and exchange rates throughout the water column of the southern California Bight. Results of circulation studies should be used to model the extent of organic sedimentation, expected changes in oxygen utilization, and expected changes in distribution of water properties, i.e., NH_3 and organisms. (Low priority)

4.2.7 Impact on Wave Climate

Research should be conducted on the items that are direct results of a wave field drastically reduced in potential energy. Such areas of research include: changes to shoreline erosion and accretion, inner harbor flushing of nutrients, changes in sedimentation patterns, biological patterns affected by low wave energy conditions, and changes to sports and recreational activities nearshore. Furthermore, it is suggested that farms might be sited in the shadow of wave diffraction patterns of existing islands along the coastline, i.e., San Clemente, Catalina, etc. Since there is a naturally occurring wave shadow fairly well defined and persistent in nature associated with the shoreline islands, the presence of a kelp farm in such regions would not substantially increase or alter the wave climate in the southern California region. Local climate effects need further definition. (Medium priority)

4.3 DESIGN-ISSUES

4.3.1 Hydrodynamic Loads on Kelp Farm

The problem of hydrodynamic loads on kelp farms may eliminate otherwise attractive sites, dictate structural design, and potentially dominate the overall feasibility of an offshore farm.

A fundamental problem encountered with several experimental kelp farm field installations is that of excessive hydrodynamic forces generated by ocean currents and large, long-period waves. The structural integrity of several kelp-farm components becomes questionable, depending upon the intensity of the prevailing ocean flow field, the local wave climate and other site characteristics. The structural integrity of the following components must be considered:

- individual kelp plants (*Macrocystis*)
- kelp attachment structure
- deep water pipe and pumps
- mooring-system components

Individual kelp plants can only tolerate currents of a few knots before pieces will separate or the whole plant is torn from its holdfast at the bottom. The near surface kelp-attachment structure (whatever design is ultimately chosen) will also be subjected to large hydrodynamic forces. Existing ocean engineering design practice permits these forces to be determined with acceptable reliability: these techniques must be applied at an early stage in order to focus on sites that are, viable from an ocean engineering standpoint. The deep water pipe and pump unit will be subject to hydrodynamic loads exerted near the surface, as well as substantial forces acting along the length of the pipe.

The dynamics of this pipe-pump system needs to be carefully evaluated to ensure its integrity in a hostile open ocean environment.

4.3.2 Factors Affecting the Survivability of Farm Structures

In addition to the maximum structural loads introduced by hydrodynamic forces, there are other, often neglected, oceanographic factors that can affect structural survivability.

Biofouling

Rapid growth of sessile fauna and unwanted algal forms can be anticipated on every submerged surface. Since the system will consist of enormous lengths of relatively small diameter elements, its surface area to volume ratio will be very high, making it especially vulnerable to the detrimental effects of fouling. These effects can take two forms:

1) Increases in hydrodynamic loads by increasing the added mass and the drag cross-sectional area of the structural elements.

2) Loss of buoyancy. Reserve buoyancy requirements must be increased to account for the growth, which is always negatively buoyant, to prevent sinking the whole farm.

Low-Stress High-Cycle Fatigue

Synthetic fiber structural members subject to millions of cycles of small deflections annually (due to water motion) fail within a few months to a very few years even under very low loadings because of abrasion or cutting of adjacent fibers. The condition can be aggravated by the presence of fine sediment in the water column and by biofouling metal parts in contact, e.g., linked shackles wear at astonishing rates under very small deflections because of rapidly accelerated corrosion at the contact point. This is analagous to fretting corrosion in bearings.

Animal attack

The most likely form of marine animal attack will be shark bite damage to the mooring lines, which can seriously reduce their strength. Since both killer and gray whales have been observed to swim within kelp beds, it must be assumed that significant structural damage could occur, especially if several animals attempt to broach close together.

The direct impact will be the loss of some portion of the structure. The downstream impacts can vary broadly:

1) Structural failures that occur on the windward, seaward or up current side can cause a ripple of failures as kelp fragments overload other down current elements.

2) Large structural elements with attached kelp, which float free, are unmarked navigation hazards and can destroy such structures as piers and drill platforms by increasing their hydrodynamic

loading under storm conditions.

4.3.3 Pumping of Deep Water

The preliminary assumptions on wave-powered pumping of deep water appear to be overly optimistic. No dynamical system for extracting wave energy has been demonstrated to remove more than about 50% of the incident wave energy that actually impacts the system. More typically, a single element system like a bearing buoy will probably be capable of extracting something like 10% of its incident energy. Attempting to load it further will critically dampen the system and prevent higher efficiencies. In no case has any known device removed more wave energy than it actually intercepts. That is, the irreducible minimum number of pumps that act as a complete wave absorber appears to be that number which it takes to stand shoulder to shoulder, touching, along the entire line of incident waves. The actual number, will be very much larger since the primary row cannot remove all the energy. Secondary and tertiary rows will be proportionately less effective because of shadowing of the primary row.

Realistic assumptions may make it impossible to produce sufficient upwelling with wave-powered pumps that are imbedded in the farm.

4.3.4 Configuration of Farm Structure

In order to maximize the life cycle of the kelp farm, consideration should be paid to the location and configuration of the farm with respect to the wind, wave and current fields. In the southern California region, predominant winds and the persistent wave fields are from the northwest essentially paralleling the coastline with a component of the wave field providing onshore wave conditions. The current field is mostly parallel to the coast but also has widely varying circular motions due to tidal component, and is more variable than the wave field.

In order to reduce current loadings the farm should take the shape of a long narrow structure with the minor axis or cross sectional width of the farm facing into the predominant current field. An elliptical shape suffices for such a design requirement. On the other hand, to maximize the ability of wave energy pumps to convert the wave energy , the farm should be oriented to present the maximum frontal area into the wave field. Since the wave and current fields are not closely aligned, a dilemma exists as to proper orientation of the farm. To avoid such a problem it is proposed that the wave pumps should be sited along the leading edge of the farm in direct exposure to the wave field on the outer perimeter of the farm. A reorientation of the farm to locate the major axis or longitudinal axis of the farm perpendicular to the wave field (assuming a wave field of singular direction) would suffice to maximize the potential for wave energy pumps. The tradeoff is to increase the loading on the system due to current loads as the frontal area in the direction that the current would increase. Such a tradeoff is not that severe since the farm consists of discrete, circular members of pipes and mooring lines. Circular members do not change frontal area in changing current fields so there is essentially no change to current loading if the farm is oriented into the wave field. The only change to loading is dependent on the specific farm mooring line configuration and the resonance dynamics of the structure.

It is known how to design to minimize the current loads are also known. The mechanics and efficiencies of wave energy pumps. Gross values of wave spectra and current magnitudes and direction are known as well.

Items that remain as unknowns include the directional behavior of the wave field and its temporal variability. Data are sparse on wave current interactions in storm conditions. Also data are minimal on operating characteristics of wave pumps. Variability in space, time and magnitude of currents is unknown.

4.4 DESIGN-RECOMMENDATIONS

4.4.1 Hydrodynamic Loading

The adequate information on the survivability of kelp plants in steady unidirectional currents or strong oscillatory currents is not available. The ability of kelp plants to withstand intense unidirectional and oscillatory flows must be defined by performing field and laboratory experiments. The effect of water pressure changes on kelp plant air sacs, due to vertical motion, should be defined.

A generic design of a kelp-attachment structure should be chosen, and forces on such structure measured with and without kelp plants attached. This could initially be done in the laboratory at small scale and subsequently in the field at full scale.

The dynamics and loads on the pump-pipe unit should be investigated, both analytically and experimentally, once the pumping system has been defined.

The mooring system should be studied at least generically at this time in order to provide feasibility and cost information, as dictated by major constraints such as water depth and hydrodynamic forces. (Medium priority)

4.4.2 Survivability of Farm Structures

Low stress high-cycle fatigue of synthetics and flex joints should be examined. Impact of biofouling and animal attack should be examined. Potential vulnerability of downstream structures should be assessed. (Medium priority)

4.4.3 Pumping of Deep Water

The following areas of study are required:

1) Effects of strong currents on the efficiency and survivability of wave-powered pumps. (Medium priority)

2) Redetermination of pump output using realistic estimates of wave energy extraction efficiencies and the effects of damping by both upwave pumps and the kelp mass. (Medium priority)

3) Consideration of alternate power schemes such as: (Medium priority)

   a) The Japanese concept of moored vessels for wave energy conversion;

   b) Pump farms separate from kelp farms;

   c) Methanol-powered pumps with the methanol produced from the methane residue.

4.4.4 Configuration at Farm - Currents and Waves

Investigation should be conducted on the ability to forecast predominant wave fields and currents for siting of farms for minimal current loads and maximum opportunity to utilize wave energy. Data are required for storm conditions on wave and current magnitudes and direction. Information is also needed on oceanographic and meteorological extreme events. (Medium priority)

4.5 OPERATIONAL-ISSUES

4.5.1 Construction and Maintenance of the Kelp Farm

To construct the 1000 square mile farm, extensive planning and time at sea is required. Numbers of 643 anchors, 1398 lines of 7 inch diameter synthetic rope and 768 buoys have been stated. Upwelling pipes built of fiberglass, 10 ft. in diameter ranging in length from 500 ft. to 2000 ft. are proposed. Pumps of such varieties as wave energy and OTEC-powered are proposed. If there are 200 such pumps for the farm (such a number is reasonable), all of this construction and installation will take an enormous amount of time.

Assuming each upwelling pipe will take 2-3 months to transport, install, and demobilize the equipment for 200 pumps, it would take four or five crews installing four or five systems sequentially a year to install 40-50 pump sites and between 4-5 years of continuous at-sea operations to install the pipes. This is an extremely optimistic projection that excludes weather down time, equipment or hardware failure, human error, and logistic problems. More reasonable estimates of 10 years should be stated.

A similar situation would exist for the implacement of the anchors and mooring lines. However, life spans of 2 years are generous for the synthetic rope components. Thus, in the 10 years it takes to install new mooring lines, 20 percent per year need replacement. So a second fleet of mooring line installers is required to charge out the mooring lines during the initial farm construction stage and will continue throughout the lifetime of the farm.

Thousands of man-hours are required on a continuous basis to construct and install the physical elements of the farm. Thousands more pieces of equipment, hardware, boats etc., are needed to perform the construction work and continuous maintenance and replacement activities. Thousands more man-hours and equipment are needed to attach and to nurture the kelp plants themselves. The potential impact of such human activities and use of fossil fuel power equipment continuously for 10-20 years at sea is an enormous environmental impact. Such impacts include air and water emissions, navigation hazards, chances of catastrophic failure, oil spills, tremendous requirements for onshore pier support, and enormous construction activity support. In addition, the quantities of materials to be implanted into the southern Californian region are massive and require whole new industries to be formulated, sited, and powered again with fossil fuel elements and high water use demands. Such material construction activities are energy-intensive (steel and concrete) and dependent on fossil fuel feedstocks (synthetic rope). Staging and assembly areas are required at the shoreline for larger farm components such as the pipes, and such land sites are not identified.

4.5.2 Selection of Farm Site

Several factors must be considered during the site selection process for kelp farms in order to mitigate potential environmental problems. Both existing and projected ocean usage is well documented through Coastal Zone Management Plans, OCS lease sales, navigation charts, and many other sources of information. No criteria or model, however, is available upon which the competing uses can be summarized and ranked. Another unknown at this time is the size or configuration of the offshore kelp farm.

It is envisioned that some approach be developed for ranking the available spaces for kelp farming. This approach could include the following steps. First, the development of both general and specific screening criteria. These criteria would address scale, distribution and configuration questions from a resource point of view including the geological, meteorological, physical, chemical, and socioeconomic features of the site. Second, a detailed evaluation of features within a larger region would be needed to determine which site specifically should be chosen. Finally, a more specific evaluation of effects based upon site/farm interactions would be required. This evaluation would include effects of the farm, i.e., air emissions, redistribution of ocean properties, farm releases and obstacles to shipping effects of the processing plants and transportation impacts (excess ship traffic, ship releases, etc.).

4.5.3 Toxicity of Waste Material

A major operational issue is related to the potential toxicity of the processing plant waste materials. If these wastes are returned to the offshore farm and disposed there, there is a potential for bioaccumulation and subsequent shifts in the biological communities. Furthermore, the character of the waste material is only generally known at this time.

4.5.4 Creation of New Biological Communities

If new biological communities are created because of the normal operations of the offshore kelp farm, several potential problems may exist including: the effects on existing fishery beds, competition between the new community and the kelp farm itself, and the creation of a large biomass buildup that will be exposed to any chemical releases.

4.6 OPERATIONAL-RECOMMENDATIONS

4.6.1 Construction and Maintenance

Investigation should be conducted on the total environmental impact (air, water and land) of the construction industries required to support and build the farm. The requirements for several fleets of new construction equipment (derrick barges, lay barges, crew boats, tugs, mooring lines boats, etc.) are to be defined and the industrial capabilities assessed as well as environmental impacts defined. (Medium priority)

4.6.2 Operational

Develop and apply a practical site selection criteria that consider site features (physical, oceanographic, biological, chemical, geological), farm characteristics (size, pumping volumes, etc.) and existing/projected site usage (military zones, available harbors, etc.) (High priority)

Examine the characteristics of waste generated and develop a strategy for disposal. This would include legal regime review and development of candidate legislation. (High priority)

Carefully examine farm structure to determine which biotic releases (from kelp plants, development of nuisance species, etc.). and abiotic releases (anti-foulants, breakage, etc.) may occur. These releases should then be quantified and related to toxicity tolerance of residence species. (Medium priority)

Quantify impact of farm in terms of attraction. Outline the effects, both positive and negative including the establishment of new biological communities or changes in old ones. (Low priority)

Determine what other substances (gases, trace elements, etc.) may be released in the upwelling water. (Medium priority)

Research the legal issues surrounding kelp farms in international waters, and what the US policy should be. (Low priority)

SECTION 5

CONCLUSIONS

During the extensive discussions over the three days of the workshop, several issues were identified by the participants that need to be addressed by the GRI environmental research program. The major research recommendations from both the biological and physical/chemical group are summarized in Table 5 (Biological) and Table 6 (Physical/Chemical). These issues and recommendations cover a wide spectrum of areas including biological, physical, and chemical oceanography as well as ocean engineering. Several issues critical to the development of the marine biomass concept, as a whole, emerged from the individual working group discussions. These overall concepts seemed to dominate the workshop and may serve as the main conclusions.

First, questions arose regarding kelp productivity in an open ocean system. Efforts should be made at once to define more precisely the expected yield in offshore farms. This information is required for the projection and evaluation of several other potential impacts. It is also needed to determine the feasibility of the ocean farm concept from a biological standpoint. Since a major problem for cultivated kelp beds is to supply the farm with proper nutrients in correct quantities, the dynamics of upwelled water must be understood, especially related to nutrient availability and uptake and kelp growth and stability. Workshop participants were concerned with how much upwelled water is required to maintain desired productivity.

Second, concerns were expressed at the workshop of the stability and survivability of offshore kelp farms. Can kelp plants remain attached to a floating structure in the open ocean? If not, can the amount of drift kelp that reaches the shore be kept to socially acceptable levels? Kelp fragments and other organic particles are expected to sink from the farm and to affect oceanic oxygen budgets.

The potential oxygen depletion in the water column and bottom sediments, due to the enhanced sinking flux of organic particles, is one of the most serious problems that was identified. Therefore, a detailed assessment is needed of particulate organic matter flux from the kelp farm to deep water and sediments.

Third, critical physical/chemical issues identified from an engineering and operational perspective included the integrity of the farm structure and its associated upwelling system with regard to ocean currents, waves, climate, and other hydrodynamic properties. It was suggested that a critical test farm experiment be conducted of the farm structure, its associated wave-driven pumps and mooring system to determine the feasibility of the offshore system.

Fourth, the residuals from the anaerobic digestion process seem to pose the greatest threat to the onshore environment. Several options were suggested for disposing of or utilizing these residues including use as cattle feed and fertilizer or disposal at the farm site. Research into mitigation and monitoring of process residues could be very contributory to the ultimate success of the marine biomass program.

Finally, the overall theme of the suggested recommendations is that any energy system in the open ocean must consider the existing natural biological, chemical, and physical oceanographic features. Therefore, a thorough review of engineering designs and process characteristics by experts from a wide range of marine sciences should be conducted early in the development process.

TABLE 5. BIOLOGICAL RESEARCH RECOMMENDATIONS

Debris	Ranking
Define more precisely the kelp yield expected from offshore farming in order to evaluate potential environmental impacts of the loss and decomposition of kelp from a farm.	High
Assess the particulate organic matter (POM) flux from the kelp (due to kelp wrack, kelp fragments, fermentation residues disposal on the farm, fouling organisms) to the deep water column and sediments to determine impact on oceanic oxygen budgets.	High
Develop scenarios for disposal options or utilization of fermentation residues, including post-treatment processes, animal feed, fertilizer, ocean-farm disposal, and by-product utilization.	High
Assess the consequences of farm failure on the sea-floor and/or coastline.	Medium
Organisms	
Assess potential for entrainment of small organisms (small fish, crustaceans, and plankton) into a kelp farm's upwelling system.	Low
Assess potential of a kelp farm to restrict migratory patterns of larger marine organisms (such as whales and sharks).	Low
Communities	
Determine the relationship, positive or negative, of a large kelp farm to recreational and/or commercial fisheries.	Medium
Obtain a better understanding of the biological communities, both benthic and pelagic, expected to be associated with large offshore farms.	Medium
Biochemical/Biophysical	
Determine possible impacts of chemical treatments on the farm to control pests such as weed species, animal grazers, and fouling organisms.	Medium
Address possible changes, both positive and negative, to planktonic systems and detrital food wells downstream of the plume of upwelled water.	Medium
Investigate displacement of planktonic communities as a result of changes in light, nutrients, temperature, etc.	Medium
Consider ways to which polyculture (i.e. the intentional culture of organisms with kelp) could mitigate or modify issues such as particulate organic matter disposal, non-natural-chemical and waste additions, and organic exudates.	Low

TABLE 6. PHYSICAL/CHEMICAL RESEARCH RECOMMENDATIONS

Oceanographic	Ranking
Develop a model to determine the fate and motion of upwelled water within the farm as a prerequisite to determining design issues such as pumping rates and siting criteria.	High
Analyze data on variable and medium scale currents to enable detailed farm structural design to be carried out.	Medium
Collect and analyze data on mixed layer depth distribution from the southern California Bright waters on a seasonal and locational basis. These upper waters make up the thermocline and this knowledge is crucial in estimating the amount of water to be pumped.	Medium
Determine the effects of a dampened wave field due to a large kelp farm, on local wave climate, shoreline formation and ultimately on inshore habitats. Obtain a better understanding of local climatic effects as a result of large scaale upwelling.	Medium
Determine residence time of upwelled water.	Medium
Obtain a better understanding of the deep ocean circulation patterns which provide oxygen and nutrients to the kelp farm.	Low
Obtain a better understanding of local climatic effects as a result of large scale upwelling.	Low
Design	
Determine hydrodynamic loading on the kelp farm installations (kelp plants, mooring system, kelp attachment structure, and deep-water pipe and pumps) as a result of forces generated by ocean currents and large, long-period waves.	Medium
Assess survivability of the farm structure including fatigue, synthetics and flex joints.	Low
Study deepwater pumping in light of the efficiency and survivability of wave-powered pumps, and other pumping alternatives.	Low
Investigate various farm configurations as methods to minimize current loads and maximize the ulitization of wave energy.	Low
Operational	
Develop and apply practical site selection criteria that consider site features, farm characteristics, and site usage.	High
Examine the characteristics of the waste generated and develop disposal strategies or utilization options.	High
Investigate the environmental impact (air, water, land) of a continuous construction and maintenance period on the kelp farm.	Medium

Study legal issues associated with open ocean farms (international and U.S. policy).	
Determine the biotic and abiotic releases from the kelp farm.	Medium
Determine what other substances (gases, trace metals) may be released in upwelling the deep water.	Medium
Evaluate the legal issues surrounding kelp farms in international waters.	Low

APPENDIX A

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APPENDIX B

PHYSICAL OCEANOGRAPHIC PROCESSES

Basic Processes

The southern California Bight is an indentation in the California coast a few hundred miles across. Its outward boundary is formed by the Patten Escarpment, a linear feature that is a prolongation of the central California coast. Beyond the Escarpment is the deep sea, 12,000 feet deep. Inshore, the sea bed is formed by a series of basins and ranges rather similar to the basin and range province in Nevada and eastern California. These features, which consist of islands and banks forming the "ranges" and basins (several hundred to 6,000 feet in depth), have a dramatic influence on the circulation, chemical structure, and wave climate in the southern Califonia Bight.

Offshore from the islands the California current flows southward in a broad, shallow, highly irregular and eddying stream. An offshoot of this current forms a large semi-permanent, counter-clockwise eddy whose inshore branch flows north and west along the region between San Clemente Island and the mainland.

In winter, the California current weakens and may reverse in direction, and the eddy in the California Bight is accordingly variable on a yearly basis. Other irregularities may be associated with passage of eddies in the California current offshore.

The surface waters have their origin in the North Pacific regions. These waters are characterized by low temperatures, low salinity and high dissolved oxygen content. Beneath the California current waters and indeed sometimes extending to the surface are waters of southern origin that are characterized by relatively higher temperatures than would otherwise be found at their depths, together with relatively higher salinity and lower oxygen content. These waters in some places form a swift and concentrated stream hugging the continental slopes but in the broad expanses of the southern California Bight form wisps and patches that are highly variable from day to day as they mix laterally with the water of north origin.

The mean speed of the California current is low and extends to depths of only 150 feet. The mean current in the Bight eddy is even weaker and about as shallow. At greater depths the mean circulation is not well known but probably quite weak.

Variable and Medium Scale Currents: Tides, Vertical Oscillations, Internal Waves and Wind Drifts

The semi-diurnal component (M_2) and principal solar component (S_2) of the tide enter the southern California Bight from the south and offshore, and sweep as a wave rapidly northward. As the water flows over the Patten Escarpment and spills into the basins and around the islands or the Bight, it displaces the dense, deep water and sets up strong internal oscillations of the tidal (predominately semi-diurnal) period that propagate as internal gravity waves within the basins. The resulting currents are intense, highly variable from place to place and have strong shear in the vertical. Although approximately all of tidal period can be modulated and the current meter can be shifted by interaction with other currents and the changing stability structures within the Bight. This results in somewhat unpredictable tidal currents of irregular speeds. They have not been mapped in the detail, although, a few values have been found. The currents tend to rotate in direction during the total cycle. They have a horizontal scale associated with the wavelengths of an internal gravity wave. The vertical scale is not well known but is likely to be mainly in low internal wave model forms, that are reversing a few times from surface to bottom. Therefore a vertical profile of current through the upper 100 feet of the farm will likely show a uniform direction.

Inertial oscillations are oceanic motions set up by any shock to the ocean. They are currents that rotate in direction with time, making one complete rotation or 360^{o} in about 24 hours in the southern California Bight. They can be confidently predicted to occur when wind storms sweep over the region. In vertical profile, they tend to be uniform through the upper mixed layer and to change direction and probably weaken within the thermocline. Their maximum speeds are not known but experience offshore in the California current region suggests speeds of 0.5 knots are common in winter storms. It is not unlikely that severe storms set up currents much larger.

Internal waves of higher frequency than inertial oscillations and the internal tides are always present. They have an irregular but short vertical and horizontal structure, with maximum currents of about 0.2 knots. Typical scales are thousands of feet horizontally and hundreds of feet vertically. They may be of importance transferring momentum vertically under the farm. Another probable but undocumented feature is that they may form an internal bore as tides sweep over certain ridges.

Wind drift currents are formed in the upper mixed layer by the direct action of wind friction on the water. They typically reach speeds of 2% of wind speed.

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