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Kendall F. Haven, Mark Henriquez, and Ronald L. Ritschard

April 1979

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I. INTRODUCTION

BACKGROUND

The Office of the Assistant Secretary for Environment of the Department of Energy through its Division of Technology Assessment has initiated a comprehensive plan relating to the extensive use of solar energy technologies. The resultant program entitled, "Technology Assessment of Solar Energy" (TASE), will determine the long range environmental and socioeconomic impacts of distributed (decentralized) solar energy systems plus selected other distributed non-solar technologies. The solar technologies include: (1) space heating and cooling and domestic hot water; (2) agricultural and industrial process heat; (3) photovoltaics; (4) wind; (5) total solar system; (6) terrestial biomass; and (7) marine biomass. The non-solar technologies are: (1) cogeneration; (2) urban waste utilization; and (3) district heating. The latter technologies were included in Phase 1 because they are complementary to the distributed solar systems being studied, in that they are scaled to local energy needs compared to large capital-intensive centralized power sources. In the next fiscal year, these non-solar technologies will continue to be studied as part of another assessment study, but not TASE.

The scope of TASE includes national, regional and community levels. The Los Alamos Scientific Laboratory (LASL) is the lead laboratory for Phase I of the national and regional studies. Lawrence Berkeley Laboratory (LBL) is leading the community studies and is also assisting with the national and regional studies. Two other major contributors to the studies have been Argonne National Laboratory and Oak Ridge National Laboratory.

The primary objective of the TASE program is to determine the probable consequences to the environment and to public health and safety resulting from widespread implementation of major solar and renewable resource technologies. Analytical efforts were undertaken during FY 1978 for Phase 1 of the TASE program. The specific Phase I objective is to determine the levels of residuals most likely to result throughout the complete energy cycle facility life cycle from the utilization of each of the solar and renewable resource technologies.

This report, entitled, Marine Biomass System: Anaerobic Digestion and Production of Methane, is presented in partial fulfillment of the Phase I requirements outlined under the TASE program. Emphasis has been placed upon the selection and use of specific applications and conceptual models to develop and quantify the data. Technical system characterizations plus material, land, and water requirements have been included. The existing reference literature has been used extensively.

In addition to the technical data reported herein, cost data have been generated for the various processes and components utilized in each solar technology. The requirements for costing information basically arise from the need to compute parameters such as investment demands, employment patterns, material demands and residual levels associated with each technology for each of several national and regional scenarios. Operating residual data are also required for these computations. To perform these computations, the Strategic Environmental Assessment Simulation (SEAS) model computer program will be utilized. Computations will be made for DOE by the Mitre Corporation.

MARINE BIOMASS

A marine energy farm is one of the few biologically-based systems which has the potential of contributing large quantities of synthetic gaseous fuels to the nation's energy supply. This is especially true from the standpoint of availability of arable land, fresh water resources, and fertilizer. The California giant kelp (Macrocystis pyrifera) is a prime candidate for energy conversion, since it is efficient in converting sunlight into a fixed source of energy. In turn, kelp can be processed by anaerobic digestion or other procedures into methane. Furthermore, other by-products such as food, fertilizer, ethanol, and industrial materials can be obtained.

Two approaches to kelp conversion to methane are described. First, a large (10.56 mi^2) oceanic farm using an artificial substrate and an upwelling system to deliver nutrient-rich deep ocean water to the kelp bed is described. This system can yield as much as 50 tons of kelp (dry ash) free - DAF) per acre-year. Kelp are harvested by a specially designed 30,000 DWT ship and delivered to an onshore processing plant as a ground kelp slurry. The second system involves the use of a natural coastal kelp bed. Growth rates in this bed are stimulated by a nutrient rich sewer outfall. A conceptual model is presented for calculation of the growth rate of kelp in this natural bed which can reach 15 tons (DAF) per acre-year. The harvest activity and processing plant are similar to those for the oceanic farm system.

In the next section of this report, the overall concept of kelp production and conversion to methane is discussed. In Section III the general design of the ocean farm system is presented and discussed while Section IV contains a similar description for the natural bed system. Section V presents the capital requirements and operational labor, resources and material requirements. Section VI describes the environmental residuals created by the operation of either system and, to the extent possible, quantifies the rate at which these residuals are generated. Finally, Section VII presents the study conclusions.

II. DESCRIPTION

SELECTION RATIONALE

The concept of the Ocean Farm as described by Wilcox (1975) is used as our model for the marine biomass system. The Ocean Farm Project has been sponsored primarily by the Gas Research Institute (GRI) and the Department of Energy (DOE) as a prime candidate for the development of a major renewable energy source. Many of the major technical and economic considerations have been explored through research efforts over the past several years. Budhraja, et al., 1976, estimated that a kelp farm (10,000 sq. miles) could provide about 1660 x 10^{12}Btu (1.66 quads) of energy assuming a photosynthetic efficiency of 1.25 percent and an insolation of 1300 Btu/ft.^{2}/day (474 x 10^3 Btu/ft.^{2}/year). Since this area represents only a small portion of the open ocean, the marine farm concept was chosen for analysis.

Two major feasibility studies have been conducted by the Integrated Science Corporation and Dynatech R/D Company. The results of these studies serve as our primary data source for the description and analysis that follows. Work is currently underway in the Energy from Biomass Program (GRI/DOE) on the validation of the basic concepts involved in kelp growth and nutrition, ocean engineering and methane generation. In addition, a Quarter Acre Module (QAM) is being tested off the coast of Southern California in order to gather preliminary data for a pilot commercial farm.

A biomass energy farm must cover a large area since the efficiency of the photosynthetic process for capturing solar energy is low (Flowers and Bruce, 1977). Furthermore, there is a need for substantial amounts of fresh water and significant levels of nutrients if a land-based system is employed. In order to remove the large land and water requirements as constraints which restrict the development of competing uses of land and water (e.g., food and fiber industry), the marine system was selected for characterization. The marine farm approach requires the utilization of only a small portion of the open ocean. Bryce (1978) reported that the concept of an ocean farm which yields 52 dry tons/acre-year (sufficient to produce about 10 percent of the nation's natural gas supply) and occupies an ocean area of about 5500 square miles, is manageable. However, the technology and legal framework to support this statement have not been demonstrated and the majority opinion of technical persons contacted for this study is that such a system is not manageable with current technology.

The farm concept that will be described and analyzed in later sections is intended to include a variety of products from the harvested kelp. This will provide for flexibility during system development and market penetration. Primary attention, however, will be given to the production of methane by anaerobic biodegradation. Methane was selected as the primary product because of the following factors: compatibility with existing natural gas systems; cleanburning characteristics; and low temperature and pressure advantages. Since a large biomass farm system has certain inherent problems related to size, number of harvesting ships, and maintenance of an offshore production site, we have included for comparison a small-scale (300 tons/day) production unit utilizing natural kelp beds (see Section IV). A comparison of the systems will be given below.

III. OCEAN FARM SYSTEM DESIGN

OVERALL CONCEPT

The basic concept of a marine biomass system is to culture and harvest seaweed plants which are attached to a grid of polyethylene lines suspended fifty to one hundred feet below the ocean surface. These lines are supported by buoyancy-control structures embracing thousands of acres (Wilcox, 1975).

Marine plants require light, carbon dioxide, water and nutrients from the surface layers of the ocean. However, many of the areas along the southern California coast which would support marine algae may be nutrient-limited for as much as 6 to 9 months each year because of a lack of upwelling (North, 1977). Therefore fertilizing operations are clearly necessary to produce good yields of kelp on ocean farms. The selected process for fertilization is to pump up nutrient rich waters from depths of a thousand feet or so. While not a general consensus among researchers, Wilcox (1975) expects that resultant photosynthetic conversion efficiencies of marine systems will be higher than current terrestial crops.

The seaweeds are to be harvested periodically and converted to methane and other by-products (fertilizer, food supplements, etc.) at a processing facility located at a coastal site. Figure 1 shows a generalized diagram of the marine biomass system used in this analysis.

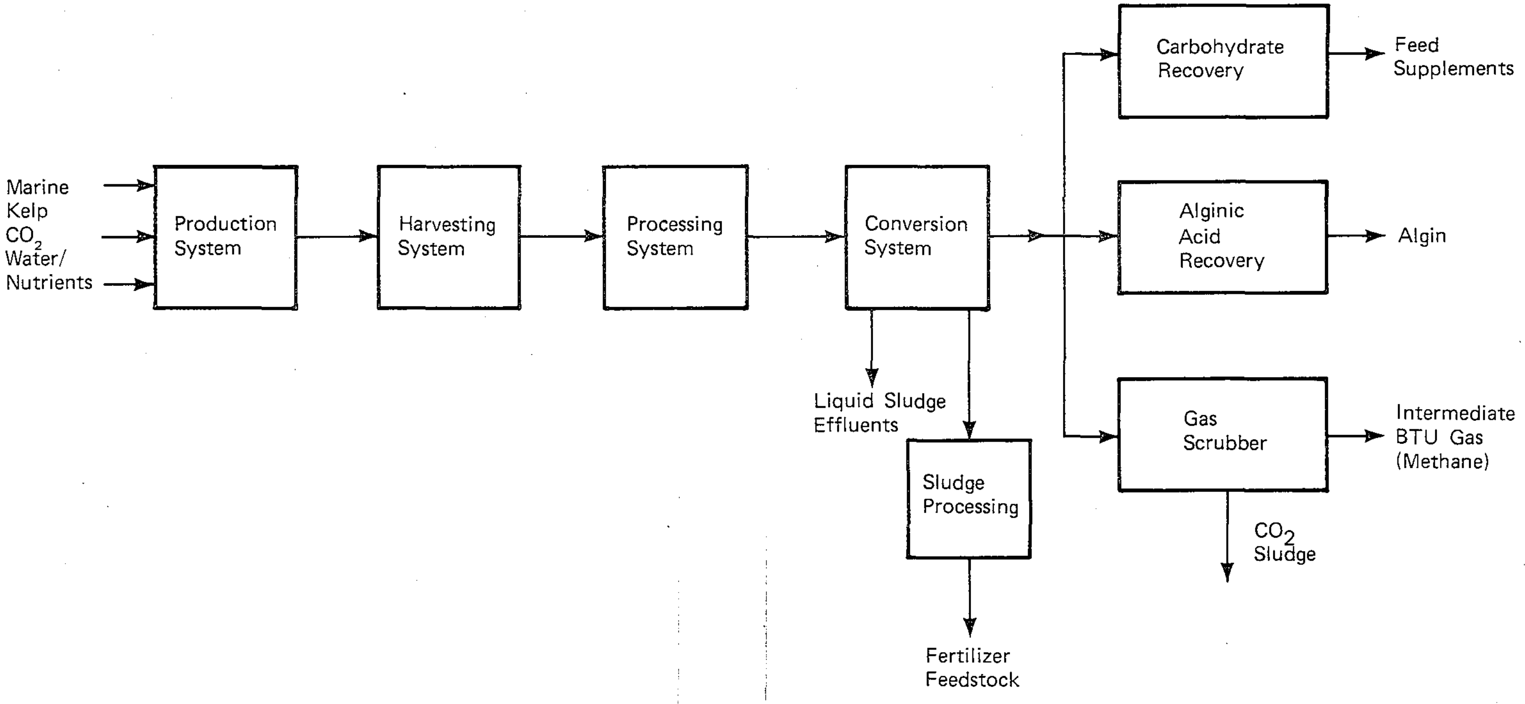

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Fig. 1. Complete Marine Biomass System

PRODUCTION SYSTEM

The California giant kelp (Macrocystis pyrifera), which grows along the coasts of California, Mexico and New Zealand was selected as the biomass source because it is one of the world's fastest growing plants and has been cultivated on an artificial substrate. The reproductive cycle is well understood and in nature it is believed that the plant will reproduce its own weight every six months or so (North, 1971). Macrocystis kelp beds have been harvested mechanically for over 60 years along the southern California coast. In the biomass farm system, the plants will be harvested every three months with no replanting expected to be required.

Of primary importance to the basic system is the determination of yield. In general, all aquatic plants have the same basic physical requirements and biological limitations for growth. The physical requirements for growth include light, which is affected by plant density and water temperature, and nutrients, which are controlled by water circulation.

The practical value for aquatic biomass production, on a full year basis, is reported to be 8 dry ash-free tons/acre/year which includes 6.7 tons of organic matter/acre/year (Clendenning, 1971). Klass (1977) reported from laboratory scab efforts, however, that anchored giant kelp may be expected to yield as high as 49 dry tons/acre/year. This assumes that nutrients are supplied by the upwelling of deep nutrient-rich water. Nitrogen, an element which most often limits the growth of marine plants, is required at levels exceeding 3 microgram-atoms per liter (North, 1977). The significance of other micro-nutrients such as manganese and iron in the controlled growth of kelp is unknown at this time.

The farm substrate proposed by Wilcox (1975) is composed of flexible triangular modules, which are maintained at 34 meters. Each module is held in place by an anchoring system. Nutrient-rich water is upwelled from about 300 meters by some type of on-site pump in large volumes (about 1.5 x 10^9 gal/square mile/day). Wilcox (1975) reports that the upwelling system would require relatively little power, probably less than one horsepower per acre-foot/day. He suggests further that the needed power could be provided by wave or wind energy.

The kelp plants are attached to the substrate at a density of one plant per 34 square meters. It is assumed that harvest of this crop would be possible within a period of four years. North (1971) reports that kelp plants under cultivation do not appear to exhibit natural aging. Plants only need to be replaced when damaged by storms, killed by disease, or injured by predators.

A test farm design was performed by Global Marine Development, Incorporated in California. The design parameters of such a system are outlined in Table 1 and represent an optimistic or ideal operation scheme. The test farm is designed to support approximately 100 adult Macrocystis plants. The base of these plants will be maintained at a depth of about 60 feet. The plants will grow up to the surface and form a canopy layer which will float on the surface. The test farm will have the capacity for providing upwelled nutrient-rich water from a depth of 1500 feet. Conventional diesel engines will be used for power. The test structure will be positioned in water (2000 feet deep) by a three point catenary mooring system (see Figure 2).

In order to satisfy the physiological requirement for maintaining a nitrogen concentration in the farm complex of 3 μg-atoms/liter for deep water having a concentration of 30 μg-atoms/liter, a flow rate of approximately 9000 gallons/minute was needed (Bryce, 1978). This upwelling rate is made necessary because below that level the nutrients would be transported out by the currents about as rapidly as they are brought to the surface. The test farm employed a two foot diameter upwelling pipe, which was set at 1500 feet in order to reach the maximum stable level of nitrogen concentration. Figure 3 depicts a general arrangement of such a test farm. Furthermore, high density polyethylene pipe was selected for the model system, since this material is flexible and has low mass and weight.

The test site selected for the Marine Farm was located approximately five miles off Laguna Beach in southern California. This area has site parameters such as depth, waves, currents, wind, and bottom conditions that represent a potential large farm site, but do not reach the extremes of other offshore locations. In addition, deep water nutrients and surface water temperatures are available that are within the required tolerance range of Macrocystis.

Table 1

Baseline Design Parameters

Marine Biomass Production

- Sea Farm System -

Parameter	Average Value
Farm Area	11 square miles[a]
Kelp Composition (Dry Weight) Volatile Solids Composition	Ash 38 - 45% Volatile Solids 55 - 62% Carbohydrates (∿48%) Algin (31 - 41%) Cellulose (5 - 14%) Protein (8 - 12%) Fats (0 - 8%)
Biomass Yield	25-70 tons dry ash-free (DAF) acre-year
Energy Content	8000 Btu/lb. (DAF)
Upwelling Depth	300-500 meters
Surface water temperature	20 °C (or less)
Nitrogen (NO_3) at 300 M depth	25-30 μg-atoms/liter

Source: A. Bryce, 1978

[a] Farm area for 1000 ton/day kelp operation

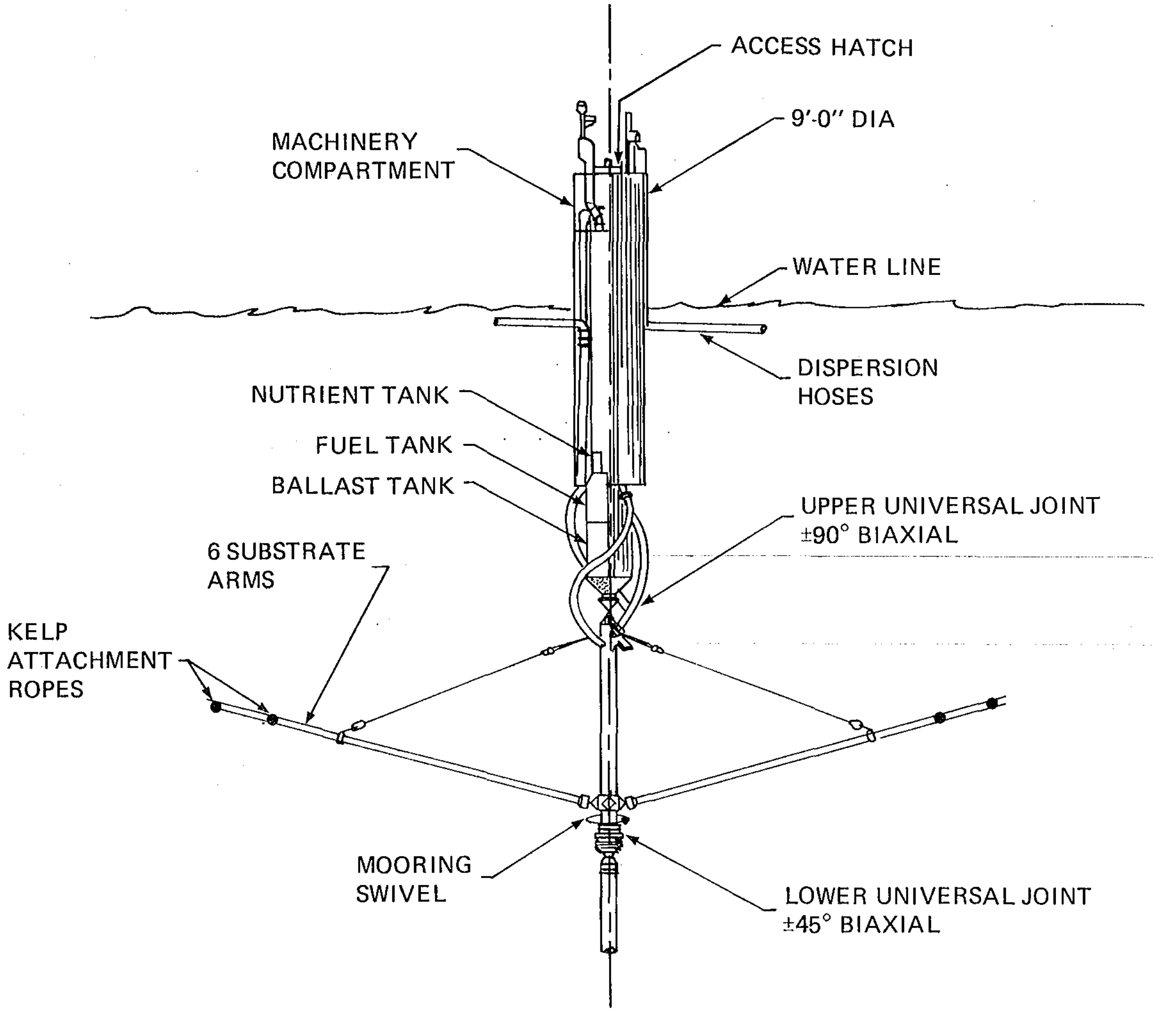

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Fig. 2. Test Farm Detail Profile

Source: From Bryce, 1978.

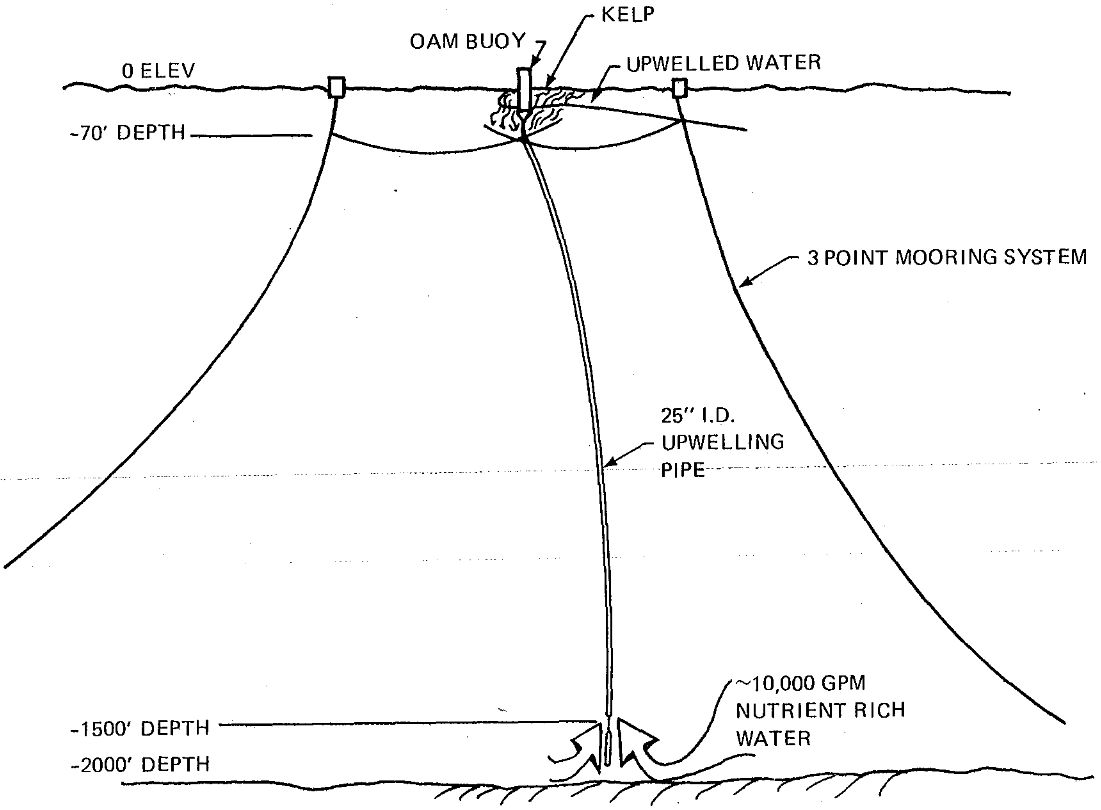

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Fig. 3. Test Farm General Arrangement

Source: From Bryce, 1978.

HARVESTING

In the marine farm designed by Wilcox (1975) the standing crop is harvested by special ships about six times per year. These vessels are patterned after the Kelco Company design, which have been 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. We assumed that the sea farm system would include some processing on the harvesting vessels. For the natural-bed system, the processing would be done entirely at an onshore processing site.

PROCESSING

The degree of processing necessary to prepare kelp for conversion into usable fuels is related to its water and ash content. Macrocystis typically has a high water content, about 87.5 percent (Wilcox, 1975). The ash content of dry seaweed is typically about 40 percent which may cause difficulty in subsequent conversion to various products (Leese, 1976).

A substantial reduction in water content would minimize shipping costs. If such processing is done at sea, a reduction in the capital costs associated with onshore sites would result because of the reduction in storage requirements.

A problem may arise, however, with drying kelp for transport. Since about 35 percent of the carbohydrate content is dissolved in water, most of it is lost in the drying process. If the food value of kelp is as much as 15 times greater than the energy resource value, then we may be saving capital on one process while losing it on another (Schneider, 1978).

With regard to ash content, it may be necessary to reduce the level of ash in order to maintain a viable culture for subsequent digestion or fermentation (Hart, et al., 1978). Since kelp ash consists principally of water soluble salts, some market may exist for such products as potassium, calcium and magnesium, since incremental system cost for removing these chemicals from the process stream would not be large.

The degree of mechanical and chemical pre-treatment necessary for increasing kelp separation and digestion has not been fully defined. A process developed for this analysis begins by shredding the wet, harvested kelp by means of hammermill-type grinders. Bryce (1978) estimated that about 1.1 kWh/ton of raw kelp is required to produce properly-sized particles from wet kelp. Next the shredded kelp is treated with a calcium chloride solution heated to 95°C. The material is then pressed (100 pounds pressure) to remove salts and excess water. The resulting mixture acts as feedstock and is fed into the anaerobic digester. Figure 4 illustrates a schematic diagram of a shore-based processing plant.

CONVERSION

The conversion of kelp to methane has been described in previous studies (Wilcox, 1975, 1976; Bryce, 1978; and Chynoweth, et al., 1978). As mentioned above, there is no standard procedure for pretreating the kelp. Several separation steps are usually used to segregate the electrolytes, carbohydrates, water and volatile solids. The soluble sugars that are pressed out could be fermented to ethanol. The volatile solids (≃60 percent) go into a heated air-tight digester where methane and carbon dioxide are produced. The feedstock is decomposed over a period of 7 or more days by bacteria in the absence of oxygen. A waste sludge, high in nitrogen, will also result. This material after further processing could be used as fertilizer feedstock.

Energy recoveries of methane on the order of 4.5 to 5 standard cubic feet per pound of volatile solids (SCF/lb. v.s.) have been obtained with 55-60 percent conversion of volatile solids (Chynoweth, et al., 1978). Table 2 illustrates performance data for anaerobic digestion of various types of biomass. Bryce (1978) reported that work is underway to increase the loading rate from 0.1 lb/ft^3 to 0.3 lb/ft^3 and to reduce the retention time from 18 days to 10 days. In Table 3 are listed the various parameters that are being achieved in recent methanation process development work.

Figure 5 illustrates the materials and energy flow for the kelp-to-methane system. The system begins with 100 pounds of wet kelp that has been converted and drained of water. This quantity of kelp has an estimated energy content of about 8 x 10^3 Btu/lb DAF. Assuming a methane yield of 4.5 SCF/lb. added volatile solids; an output of about 31.5 SCF of methane is obtained with an energy recovery efficiency of 55.5 per-

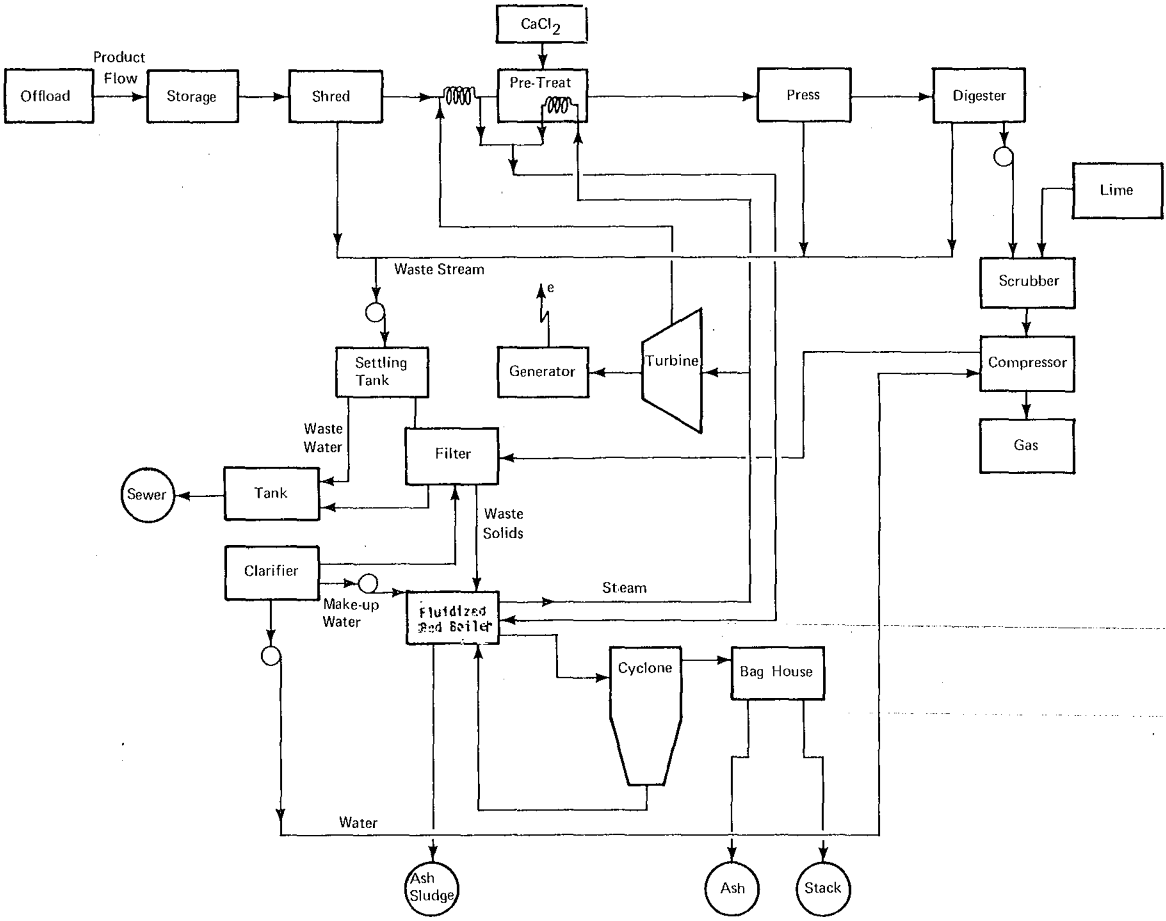

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Fig. 4. Kelp to Methane Processing Plant Schematic

Table 2

Performance Data for Anaerobic Digestion of Various Types of Biomass

Reference	Biomass Type	Methane Yield SCF/lb VS added	VS Destruction, %	Special Conditions
IGT, 1977	Raw kelp	4.5	48.0	T[c] = 35, L[d] = 0.1, DT[e] = 18
Pfeffer[13]	MSW-Sludge[a]	2.42	51.8	T = 55, DT = 20
Pfeffer[13]	MSW-Sludge	1.58	53.4	T = 35, DT = 20
McCarty *et al.*[12]	MSW-Sludge	3.26	33.0	T = 35, L = 0.23, DT = 15
Ghosh and Klass[6]	MSW-Sludge	3.80	58.5	T = 35, L = 0.14, DT = 12
Klass and Ghosh[11]	Grass mixture	3.10	----	T = 35, L = 0.12, DT = 16
Bryant *et al.*[9]	Feedlot cattle waste	4.10	47.0	T = 60, L = 0.54, DT = 9
Bryant *et al.*[9]	Feedlot cattle waste	2.74[b]	35.8	T = 60, L = 1.62, DT = 3
Converse *et al.*[10]	Dairy manure	3.33	43.1	T = 35, L = 0.27, DT = 15

[a] Municipal Solid Waste-Sewage Sludge.

[b] 4.15 SCF CH_4/ cu ft culture (highest rate of methane production in the literature).

[c] Temperature, °C.

[d] Loading, lb VS/cu ft-day.

[e] Detention Time, days.

Table 3

Biomethanation Parameters

Methane Yield	$\frac{\text{4.5 - 5 Standard Cubic Feet}}{\text{Pound Volatile Solids}}$ $\frac{\text{(SCF)}}{\text{(lb. V.S.)}}$
Detention Time	10 - 18 Days
Volatile Solids Converted	65-70%
Loading Rate	0.1 - 0.3 lb. VS/ft^3
Temperature	35°C
Volume	65% Methane 35% Carbon Dioxide
Energy Recovery	55.5%

Source: Chynoweth, D.P., _et al_, 1978.

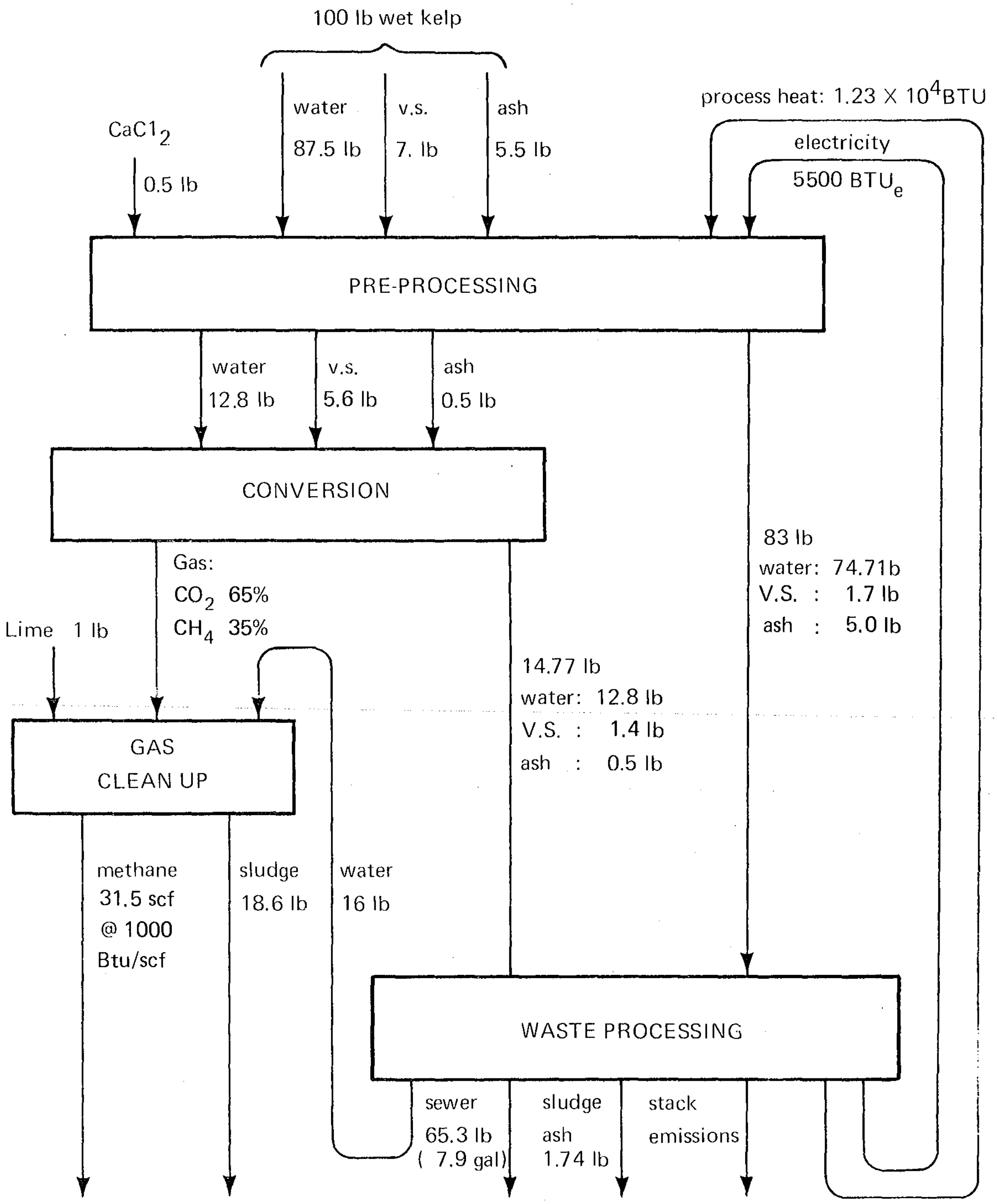

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Fig. 5. Materials and Energy Flow
- Kelp to Methane System -

cent. This energy yield represents an output of about 31.5 x 10^3 Btu of methane gas from the initial input of raw kelp. These results are based upon anaerobic digestion in laboratory-scale digesters using mesophilic operating conditions (Chynoweth, et al., 1978). If one were to scale this demonstration to the 10^{12} Btu level for comparison with other solar technologies, an estimated input of 1.59 x 10^6 tons of raw kelp would be required. It may not be valid at this time, however, to extrapolate the successful bench-level studies of kelp conversion to levels producing significant amounts of energy on a national level.

Although this report has emphasized the production of methane gas as the primary product, other byproducts are possible. In fact, if the marine biomass system is to make a major contribution to the energy sector, it will probably require that these other products be processed as well. Potassium chloride, sodium sulfate, sodium carbonate and other salts are possible moderate value products. Several industrial gum materials such as algin, fucoidan and laminarin are available. Algin has been extracted from kelp for profit for many years and has many uses in the food and chemical industry.

Since all of the carbohydrates in Macroscystis are polysaccarides, they contain sugar molecules which may become economically viable food products. Wilcox (1975) reported that a probable high value product is a feed supplement for ruminant animals (e.g., sheep and cattle).

As noted in Figure 1, the sludge residue from the methane conversion system could be processed to a low to moderate grade nitrogen fertilizer. Furthermore, if the sludge were sterilized, it could be used as a feed substrate for single-celled, protein-producing micro-organism.

Finally, various mariculture systems as well as various sport fisheries may be established around the open ocean marine farm. These fisheries can make both positive (additional products and food resources) and negative (nuisance, kelp destruction) contributions to the farm operation.

IV. NATURAL KELP BED SYSTEM

INTRODUCTION

Algae have long been known as ubiquitous constituents of nearly every body of water. Because of their fast reproduction rates, algae have historically received attention for their role in clogging filters and producing objectionable tastes and odors.

The results of natural or induced algal blooms are well known and have tended to obscure the fact that algae possess a variety of biophysical properties which have already been transformed into a cash crop and the basis of a multimillion dollar industry.

There are several ways in which the use of algae can make a significant contribution. In California, the use of micro algae in waste oxidation systems account for a significant fraction of the State's installed secondary municipal water treatment facilities. Secondly, because of their high protein content the cultivation of algae for human and animal food is a growing industry in several counties. Finally, methods have been reported which optimize algal growth rates so that the harvested algae provide a substrate for the production of high quality synthetic natural gas (SNG) via anaerobic decomposition by mixed bacterial cultures (Oswald, 1976, 1977; Uziel, 1976; Golueke, 1977).

NATURAL KELP BED SYSTEM

One such proposal for producing usable amounts of algal substrate for an SNG process involves increasing the yield capacity of existing near and off shore kelp beds. In California, these beds already support a sizable harvesting effort based on Macrocystis pyrifera. As stated previously, these brown algae possess a number of characteristics which make them the current choice in mid-latitudes for SNG production.

Limiting factors in the natural bed cultivation of Macrocystis are likely to be a function of nutrient availability such as nitrogen phosphorus and temperature distributions. Goldman and Wilson (1977) reported that while at low growth rates, temperature increases have little effect, at high growth rates a temperature increase of 3.5°K will decrease growth rates by a factor of 10. North (1975) reports that the maximum temperature for offshore beds is 68°F, at which deteriorations in the product become noticeable. These factors have limited the annual state harvest of Macrocystis to about 150,000 tons of wet weight.

While the economics of alginate recovery have justified harvesting existing beds up to 200 miles from the kelp processing plant, it is probable that economically viable energy production would require both higher yields per acre than the current average of 6 wet tons/acre/year and the use of close-in beds as the return for energy products is lower than for alginate.

The direct relationship between amounts of available nutrients and specific yield/area has resulted in three general approaches. They are mechanical upwelling, passive diffusion and co-siting. Because the cost of secondary sewage effluent is negligible with respect to its nutrient content co-siting kelp beds near existing sewage outfalls could provide a cost effective method of increasing yield. A further advantage of a co-sited system is that the sewage effluent receives an added degree of treatment through biological oxygination and thereby has a fraction of its biological oxygen demand (BOD) reduced. This would result in a cleaner discharge and reduced environmental impacts on marine ecosystems.

Several methods are available for calculating probable algal productivity values for such a system. Chemical analyses of Macrocystis show that on an ash free dry weight basis it contains 43 percent carbon, 1.6 percent nitrogen, 5 percent hydrogen, 21 percent oxygen, and .3 percent phosphorous. The Oswald sotichemical method allows us to normalize the N content to 1 and divide the percent composition by the molecular weight of the given substance; thus we arrive at a general formula which is:

$$C_{662.770}H_{7.96}O_{2.07}N_{1} \qquad (1)$$

It is helpful to know the ratio of O_2 produced per unit of cell mass. From formula 1, we find that the empirical formula weight of Macrocystis is 7992.36 mg. Since algae produce O_2 via photosynthesis, 2.65 mg O_2 is produced for each mg of macroalgal cell material. This compares favorably with the 1.6 mg/g Oswald (1977) reports as an average for microalgae.

If nutrient limited growth conditions are assumed, it becomes desirable to know the maximum cell concentration that a given sewage can support. Jenks and Adamson (1974) report on an annual average BOD for Hayward of 78 mg/l, with sewage flow of 100 gpd. We find that an algal population density of 29 mg/l over the bed can be supported on the nutrients in the sewage fraction alone. This is in addition to the existing seawater growth potential and is therefore a minimum growth value.

From this:

$$\frac{\text{BOD Sewage}}{\text{Algae } 0_2 \text{ production}} = \text{populations density} \qquad (2)$$

$$78/2.65 = 29.43 \text{ mg/l}$$

In applications where algae are being fed on sewage, growth rates are generally considered to be light limited. Most of the current work for calculation of macro algae growth rates are based on work by Oswald (1976). From these relationships, it is now generally accepted that light limited algal productivity is related to the exponential decrease in light intensity as it penetrates a body of water. This relationship is described in the Beer-Lambert law:

$$Ix/Io = e^{-\alpha Cd} \qquad (3)$$

Nomenclature used in this section is shown in Table 4.

Since the relation is wave length dependent, solar applications require its integration over the entire visible light spectrum from 400-700 nm. (Considering algal photosynthetic efficiency and concentration-depth relations). For monochromatic light algal productivity per unit time can be approximated by Wilson's method. (Wilson, 1977):

$$P = \left[\bar{K}/J\ E_m I_s\right] \ln \left[\frac{I_s + I_o}{I_s + I_o e^{-\alpha Cd}}\right] \qquad (4)$$

While growth rate at a given depth is given by:

$$\mu_d = \hat{\mu} \frac{I_d}{I_s + I_d} \qquad (5)$$

Table 4

Nomenclature for Algal Growth Calculations

Parameter	Definition
I_o	incident light intensity (cal/cm^2-min)
I_s	saturation light intensity (cal/cm^2-min)
$\hat{\mu}$	Maximum (saturation) growth rate (mg/l-d)
I_d	light intensity at depth$_d$ (cal/cm^2-min)
C	algal concentration (mg/l)
α	extinction coefficient
AC	absorption coefficient
I	visible irradiance (cal/cm^2 - min)
E_s	efficiency of light utilization
μ_d	specific growth rate at depth$_d$ (mg/l-d)
d	depth (cm)
P	production per unit time (wet) (kg/m^3-yr)
E_m	thermodynamic efficiency
K	time constant
J	algal heat of combustion (6 Kcal/gm)
DR	dilution rate = $\frac{\text{flow rate}}{\text{culture volume}}$

For the purposes of this study, equation (5) was integrated over the depth range to 65 feet typical for Pacific coastal kelp beds). The results in an enriched (light limited) system show that kelp productivity will vary from 18Kg/m^3-yr at a depth of 21m to 89 Kg/m^3-yr at maximum light intensity.

In a continuous flow system, the dilution rate (DR) can be related to productivity by (Wilson, et al., 1977):

$$DR = P/Cd \tag{6}$$

When other variables have been established for a given light spectrum and system in equation (5) (e.g., K, J, E_m, I_s and α) productivity is dependent upon the product of Cd. Thus, maximum productivity can be determined from a unique combination of C and d. Applying this to equation (6), a dilution flow rate for maximum productivity can be established, which for continuous flow systems will equal the growth rate maximum of the system. Thus input nutrient (sewage) flow characteristics can be determined to maximize productivity in a given kelp bed based on existing contours and kelp concentrations. Conversely, optimal cell concentrations could be estimated for a known sewage flow rate. If, for example, a one acre bed with average depth of 60 feet received a sewage flow of 7.6 x 10^7 l/day, maximum productivity at 21 m would require a cell concentration of 5.5 mg/l, while at 1 m would require 39 mg/l. Considering the sewage contribution of 30 mg/l and non-enriched seawater growth potential of 27 mg/liter, it becomes clear that the use of sewage as a kelp nutrient source can, in the absence of other factors, be expected to more than double the harvest capacity of existing beds.

KELP GROWTH MODEL

In practical application, nutrient distribution will be non-uniform with respect to the surface area of the bed and cultures may not be continuously light limited. It is reasonable to assume that nutrients will form a velocity related profile with maximum concentrations confined to a zone immediately downstream of the outfall diffuser. Nutrients can be expected to decrease as a function of distance from the point of origin. Profile shape will be related to bathogmetry, current distribution direction and magnitude, temperature and salinity gradients. Finally, the use of microalgae growth equations have implicit limitation in describing macroalgae growth characteristics, yet can indicate the basic trends and directions of algal growth.

The composition of the sewage effluent can be expected to change with the season and locale as indicated in Tables 5 and 6. The variation shown on Table 6 results mostly from seasonal canning operations, which are common in some areas of the state. Heavy metals, which are an indicator of canning operations, can have a toxic effect on kelp. Molybdenum and zinc are most usually mentioned as inhibitory substances which should not be present in sewage for best results. The long range effects of heavy metals discharge on kelp beds has yet to be studied. Finally, there is the question of grazing or other damage caused by associated organisms. North (1975) has identified 15 plant and 14 animal species which have established themselves in marine kelp beds.

For these reasons, it is almost certain that enriched natural kelp systems will achieve maximum productivity only over a fraction of their total volume. For an effective bed area of 3.2×10^{10} m^3 (or one acre x 60 ft. depth) and a productivity of 20 Kg/m^3 and with only 1/100 of the total volume supporting optimum growth, 1873 short tons/day could still be produced.

While it may be argued that sewage grown kelp would be unfit for ingestion due to the nutrient source, giant kelp could still provide a valuable substrate for synthetic natural gas production. This is a positive contribution to the U.S. energy balance in addition to utilizing a potentially valuable resource, municipal secondary sewage effluent.

A mathematical model of kelp growth based on the foregoing discussion was developed for a small (~ 1 sq. mi.) kelp bed in central California coastal waters. A sewage outfall into the bed was assumed so that kelp growth became light limited. The major environmental parameters analyzed within the model include: incident solar radiation (Io), solar intensity at which photosynthesis is saturated (Is), specific absorbance of *Macrocystis*,

Table 5
Characteristics of Selected Northern California Discharges
(1973-75 Data)

	Discharge			
	San Leandro	Ora Loma - Castro Valley	Hayward	Union
1. Flow				
Average Dry Weather Flow (mgd)	7.4	13.9	10.6	5.1
Peak Annual Flow (mgd)	22.0	68.0	31.0	11.9
Average Per Capita Flow (gcd)	90	99	93	85
Average Industrial Flow (mgd)	3.4	0.5	1.7	1.8
2. BOD				
Average BOD (mg/l)	290	302	286	278
Average BOD (pcd)	0.22	0.23	0.22	0.17
Average BOD (lbs/day)	17,900	35,000	25,300	11,760
3. TSS				
Average TSS (mg/l)	421	326	346	240
Average TSS (pcd)	0.24	0.26	0.21	0.15
Average TSS (lb/day)	26,000	37,800	30,600	10,100

From: Henks and Adamson, 1974

Table 6

Seasonal Variation in One Sewage System[1]

Month	Flow (mgd)	BOD (lbs/day)	BOD (mg/1)	TSS (lbs/day)	TSS (mg/1)
1972					
November	12.35	5633	53	5730	56
December	11.61	2110	22	4316	46
1973					
January	13.64	3415	31	6486	60
February	15.72	2697	22	6167	49
March	13.95	2445	21	6493	54
April	11.49	1765	19	3760	40
May	11.06	1560	19	3250	40
June	10.05	2935	35	5783	69
July	12.05	4720	48	11,300	111
August	18.15	56,000	391	24,680	172
September	17.37	30,000	230	16,900	131
October	12.31	5200	49	9030	86
Annual Average with canning	13.3	9873	78	8658	76
Annual Average without canning (10 months excluding August and September)	12.4	3248	32	6231	61

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1. Data for Hayward, California discharge.

Source: Jenks and Adamson, 1974

temperature, heat of combustion, and the depth at which the culture is growing. All of these have been incorporated into a dynamic representation of kelp productivity per unit of farm area. By examining the system in this fashion we have been able to assess the sensitivity of production to variations in environmental factors. Also estimates of kelp yields in an ideal sewage-enriched case were developed. Because models of this type are based on a monochromatic solar input we have also been able to examine how light of different wavelengths are used preferentially at different depths.

In site specific rather than generic form these techniques would allow the simulation of such practical constraints as turbidity. A fully expanded model would also allow the calculation of rates of light utilization, photosynthetic efficiency and optimal values for depth and culture density.

For the purpose of this analysis a 'worst case' light saturation value of .03 gm-cal/cm^2-min was assumed as a base case and monochromatic incident radiation at 400, 566 and 750 nm were used. All wave lengths are in the visible range. The results, expressed as productivity (P) in mg/cm^3-day represent the total production at specific depth including the contribution of the incremental depth immediately above and is therefore a summation value. Direct values for unit production in Kg/m^{3}yr under various environmental conditions are also included. Model results are shown in Figures 6 and 7. In Figure 6, variations in production are shown as a function of incident light wavelength and of depth. In Figure 7, variations in kelp production are shown as a function of incident light intensity and depth for two values of the light situation constant, I_s.

Based on a number of successive iterations, the model provides the following insights:

1) Greater total productivity within the cutting zone (1-3 meters depth) results from the high frequency component of incident radiation but the fall-off in rate of production is minimal at mid frequencies.
2) Productivity in terms of total biomass and rate of production decreases with depth but that the rate of decrease is frequency.

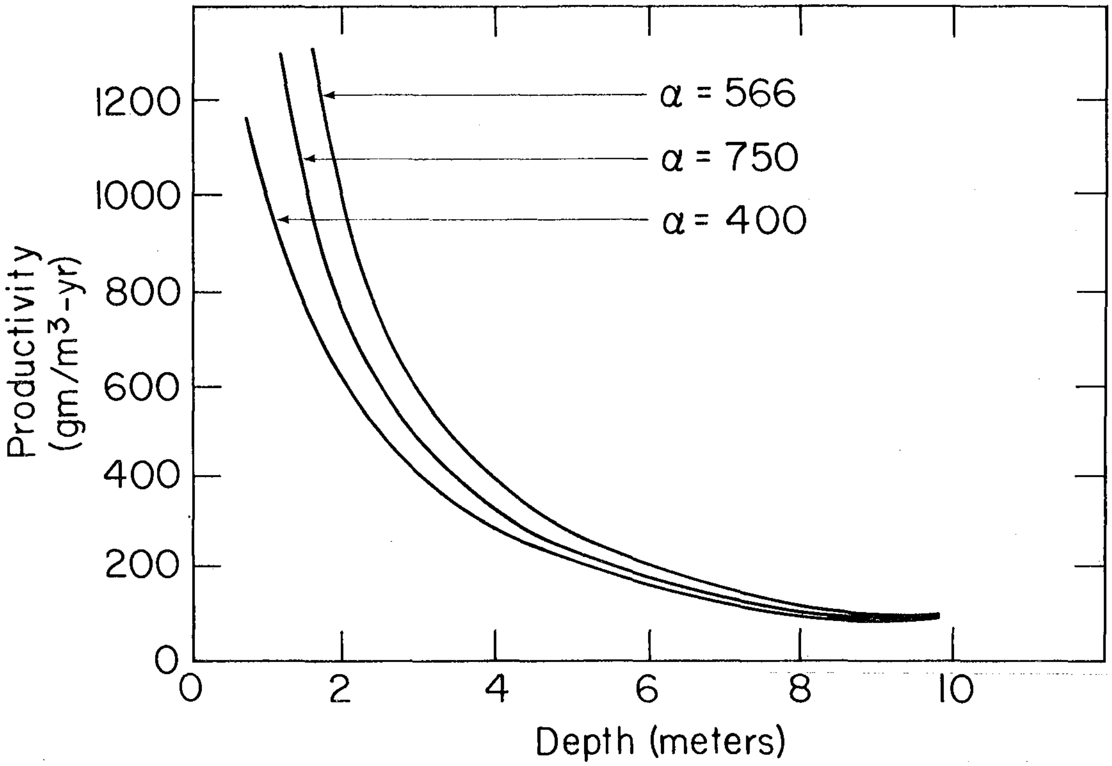

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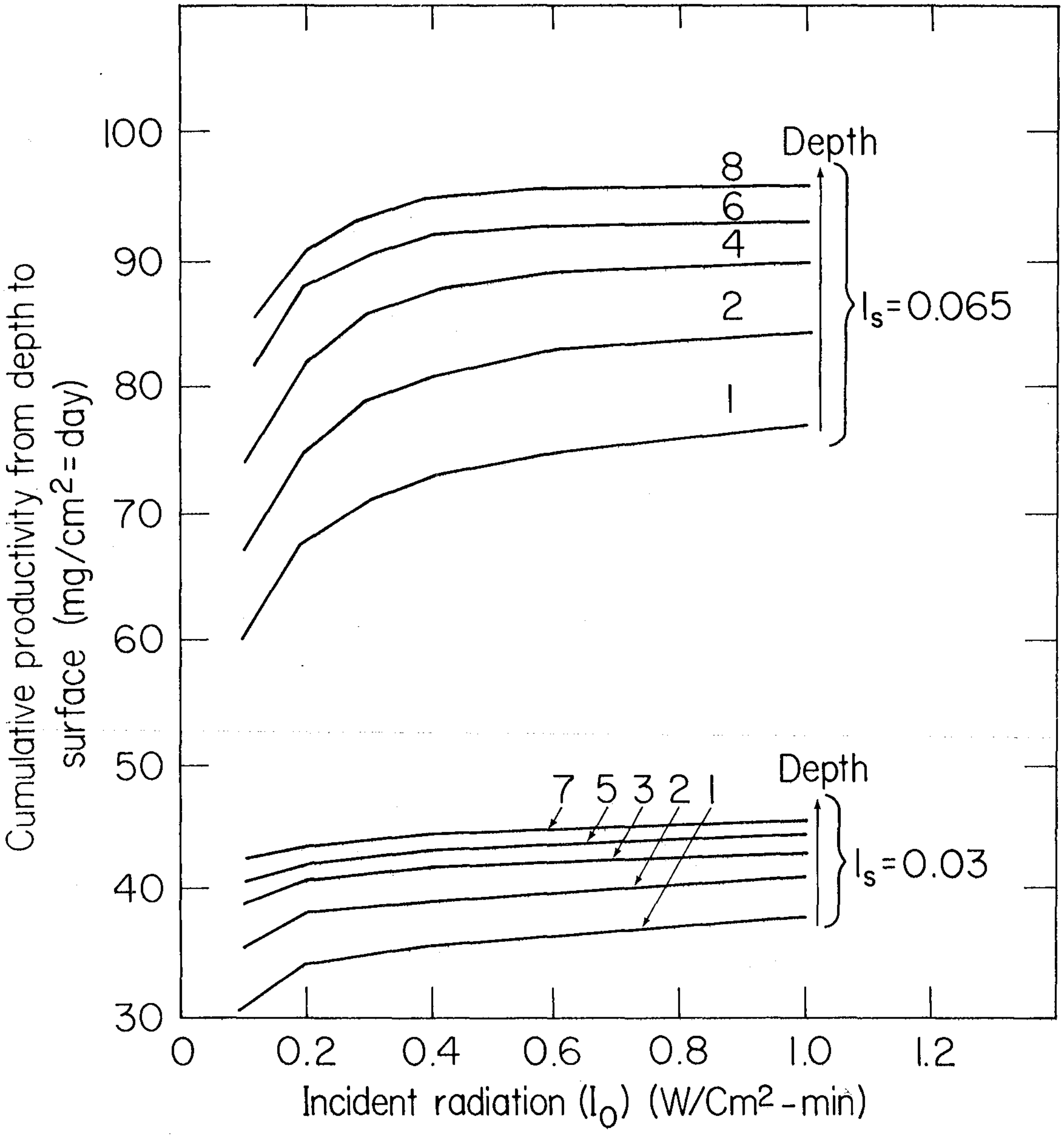
Fig. 6. Variation of Productivity as a Function of Depth and Wavelength of an Incident Monochromatic Light Source.



XBL 781-13493

Fig. 7. Variation in Kelp Production as a Function of Incident Light Intensity and Depth for Two Possible Values of the Light Saturation Constant.

3) Increasing the photosynthetic saturation intensity at higher (750 nm) wavelengths results in a large increase in total productivity at minimum incident light intensities but a substantially smaller increase at intensities close to saturation. A similar phenomenom was noted for lower wavelengths (400 nm) within the tested wavelength range.
4) Productivity yields are most frequency dependent at depths around 2 meters. As this is in the middle of the cutting zone, further study in this area may be of value.
5) These results suggest that some complex interactions take place within the cutting zone, the elucidation of which may result in a better understanding of kelp growth dynamics and ultimately larger harvests.
6) The model results indicate that a reasonable range of yields for the bed described in this section is from 25 Kg/m^3 to 30 Kg/m^3, or 3 to 4 times the non-nutrient subsidized bed yields.

A description of the natural kelp bed system using sewage treatment plant effluents is given as an alternate method of production. The harvesting, processing and conversion systems needed to transform kelp into pipeline quality gas are given in Section III (Ocean Farm System). The overall concept for both these alternatives is the same, only the size and type of production unit and source of nutrients differs between the offshore ocean farm approach and the natural kelp farm. A comparison of the capital requirements for both systems is given in Section V (Capital Requirements).

V. CAPITAL REQUIREMENTS AND SYSTEM COSTING

INTRODUCTION

The basic energy conversion system being considered in this report is the ocean kelp farm supported system. This system involves an extensive oceanic steel and plastic framework supporting the kelp plants with a series of pipes and pumps used to enrich the kelp with nutrient rich deep ocean water. A fully dedicated ship, or ships are used to harvest the kelp and deliver it to a central shore based anaerobic digestion energy conversion plant. As mentioned earlier, this sytem is both capital and labor intensive and may not be cost-competitive with alternate energy sources.

A large portion of the capital requirement for the oceanic farm system is associated with the oceanic support structure and upwelling system. These portions of the overall system are designed to facilitate both an increased kelp growth rate and a physically larger kelp bed than could be provided by natural coastal kelp beds. However neither portion is an integral part of the process of converting kelp to methane. Therefore, a second smaller kelp conversion system is also described in this report. This second system uses natural coastal kelp beds and therefore incurs neither a capital nor an operational cost for kelp growing, but produces lower yields (12 to 15 tons (DAF) as compared to 50 tons (DAF) for the oceanic farm system). Further, a system using natural kelp beds can reduce harvesting costs by avoiding the travel time to and from an oceanic farm located 100 miles or more off shore. Thus, the natural bed system is designed to reduce capital cost by taking advantage of natural kelp growth while the oceanic farm is designed to maximize methane production.

The oceanic farm system has capital costs of $1.977 billion (1977 dollars) and an annual methane production rate of 2.16 x 10^{12} Btu (14,300 tons of input wet kelp/day). The natural kelp bed system costs $5.24 million dollars (1977 dollars) and produces 4.54 x 10^{10}Btu of methane annually (300 tons of input wet kelp per day). As a comparison, the oceanic farm system costs \$9,152,902 per 10^{10}Btu of annual methane production, while the natural bed system costs \$1,149,300 per 10^{10} Btu of annual methane production.

This section presents detailed capital equipment system descriptions for both the oceanic farm system and the natural bed system. Additionally, capital cost data and annual operational cost data are presented. Both sets of cost figures are compiled by the sector of purchase for the 200 economic sectors used in the SEAS data base. Further, all cost figures represent required purchases per 10^{12}Btu of annual output capacity. Thus, since the described natural bed system produces 4.56 x 10^{10}Btu per year, the enclosed figures represent the cumulative cost of 21.91 (10^{12}Btu/4.54 x 10^{10}Btu) identical systems.

The designs and costs presented here are based on a review of a wide variety of processes, manufacturers' equipment, and previous studies both for kelp growth and utilization and for the anaerobic digestion of various low density, high water content fuels. More specifically, the oceanic farm system design has relied to a large part upon studies by Integrated Sciences Corporation and Hawaii Laboratory, Naval Underseas Laboratory (Ocean Food and Energy Farm Project, subtasks 1 through 6), by Dyna-tech, Inc. (1978), and by Dr. W. North (1973, 1977, and 1978). In addition, both systems have relied upon a number of "bench scale" research programs and previous kelp conversion reviews including: Chynoweth, Klaus, and Ghosh, 1978; Bryce, 1978; Pfeffer and Liebman, 1976; Trocano, et al., 1976; and Hart et al., 1978. However, it must be stressed that the designs and costs presented here represent neither a specific manufacturers' product or equipment specifications, nor the design presented in any specific previous design project. Rather, the system described in this report represents typical cost of equipment specifications for the conversion process deemed most likely to provide cost effective and cost-competitive methane.

NATURAL KELP BED SYSTEM

A detailed system diagram for a natural kelp bed system is shown on Figures 8 and 9. These figures show the major pieces of equipment and product mass flow rates at each step within the system. Figure 8 shows the product flow from kelp bed through the methane gas compressor. Figure 9 shows the plant subsystem which processes waste flows and, through a cogeneration system using a fluidized bed combuster, provides both the process steam and electricity required by the kelp conversion system. Below is given a brief description of each component within this system.

Harvest Ship

Only one small harvesting ship is required to supply the 300 tons of kelp required by the plant each day. The ship is designed as a 1000 DWT open cargo ship with a retractable cutter which is submerged 10 feet under the surface during harvest operations. A conveyor system is used to carry cut, wet kelp into the cargo hold. The ship uses a crew of four and averages one trip per two days and performs no on-board kelp processing.

Dock Facilities

Kelp off-loading is performed by a single shore based bucket crane. This system is used since the unshredded kelp is not suitable for slurry piping to shore, since this type of crane system is relatively inexpensive, and since off-load time is not a constraining factor for the system. Off-loaded kelp is stored in a dockside storage tank with a four day (1200 wet ton) capacity.

Shredding

A two stage shredding system is employed. First a hammermill type shredder is used for coarse size reduction of the cut kelp. A second stage grinder is used to reduce kelp size so that 70% will pass through

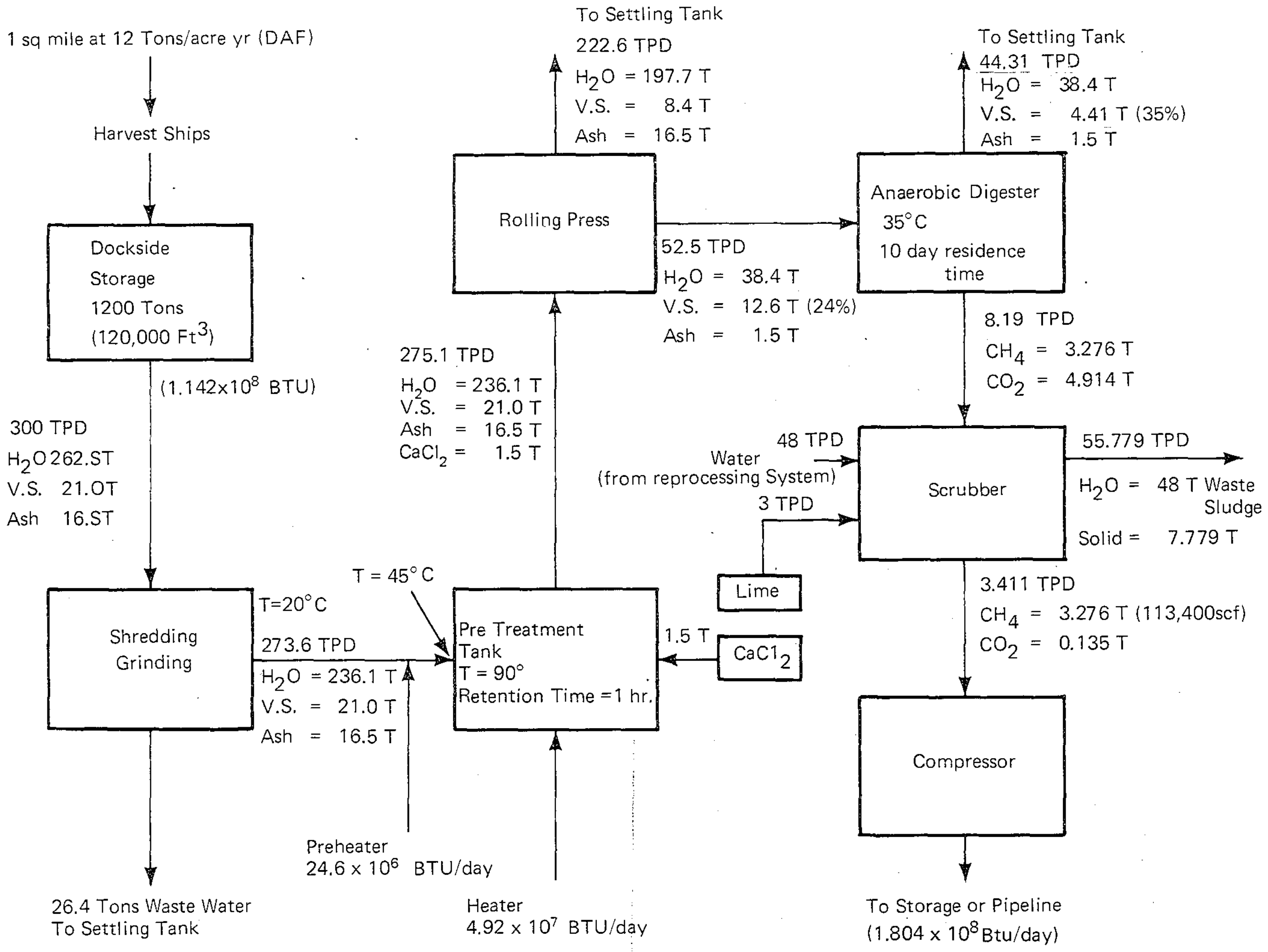


Fig. 8. Detailed Mass Balance Diagram for the Product Flow Portion of the Kelp Processing Plant.

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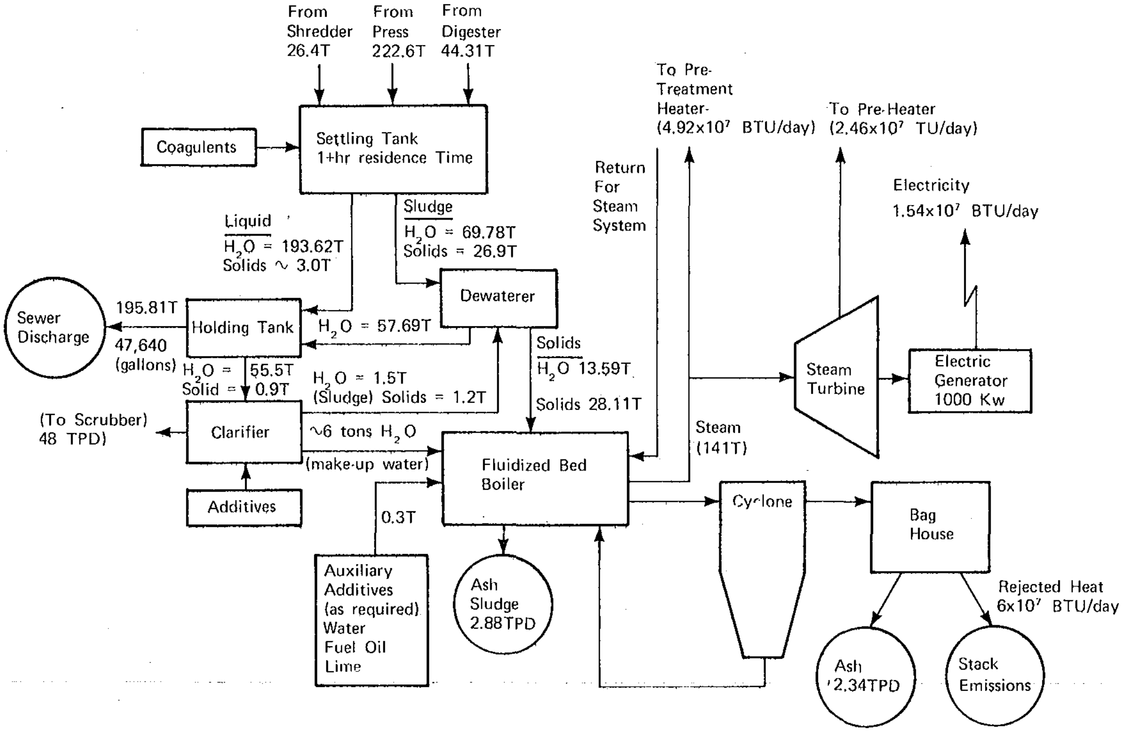

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Fig. 9. Detailed Mass Balance Diagram for the Waste Processing Subsystem.

a 4 mm mesh. A flow rate of 35 to 40 tons per hour of input wet kelp is maintained during an 8 hour work shift per day with a design capacity of 50 tons/hr. Approximately nine percent of the water in the kelp is released during shredding and grinding and is collected in a central settling tank for processing. Between 1.1 Kwhr and 1.4 Kwhr are required per ton of input kelp by this process.

Kelp Pre-Treatment

After grinding, the kelp slurry is conveyed into a "pre-heater" heat exchanger, using the waste steam flow from an on-site steam turbine to raise the kelp to 45°C from an average input temperature of 20°C. The kelp then enters an insulated pre-treatment tank where it is heated to 95°C, mixed with calcium chloride (0.5 percent by weight) and held for one hour. While in residence the kelp slurry is continuously mixed using an electric mixer motor and set of blades. The goal of this step is to facilitate salt and, secondarily, water removed from the product flow during subsequent pressing.

Pressing

The exit slurry from the pre-treatment tank is directed into rolling presses operating at 100 psi with a capacity of 50 tons per hour. Rolling presses were selected because of their compatibility with a continuous feed digester. The waste stream from the presses contains approximately 40 percent of the volatile solids, 92 percent of all ash and salts and approximately 80 percent of all water. The remaining product cake contains 24 percent volatile solids for feed into the digester.

Anaerobic Digester

A concrete insolated anaerobic digester is fed at a density of 0.3/lb. ov V.S. per ft^3 and is maintained at a temperature of 35°C. Residence time within the 1.2×10^6 ft^3 tank is 10 days, and electric motors are used to provide continuous mixing. With this temperature, residence time combination approximately 65 percent of the volatile solids will be converted to gas, and the gaseous discharge will contain approximately 60 percent CO_2 and 40 percent CH_4 (Bryce, 1978; Dynatech, 1978).

Gas Cleanup

A scrubber is used to reduce CO_2 in the gas stream, containing 1.13 X 10^5 scf of methane, by 96 percent. A compressor with an input capacity of 1.50 X 10^5 scf/day and an operating pressure of 1000 psi is used to feed the kelp produced methane either into gas pipelines or into on-site storage tanks.

Waste Processing

All waste streams are directed into a central large settling tank where average residence time is approximately 1.1 hrs. The sludge feed from this tank is dewatered with a partial vacuum filter and fed into a fluidized bed combuster. Liquid is drawn off the top of the settling tank and fed into a second holding tank. Water is topped off of this tank and pumped to a clarifier, to supply plant process water requirements.

Sludges at approximately 67 percent solids are burned in a fluidized bed combuster with a lime bed. Fuel oil is used as a back-up fuel as required. The output steam flow from this combuster (141 tons/day) is capable of supporting both the process heat requirements of the pre-treatment tank and a 1200 Kw electric steam turbine/generator system. This electric system is capable of supporting all plant electric demands (1.74 x 10^7 Btu/day electric). Excess electric power is stored in a conventional lead-acid battery to maintain light, controls, monitoring equipment and mixing motors during off-hours.

Finally, the waste steam stream from the turbine is used to pre-heat the kelp slurry before entering the pre-treatment tank in a separate heat exchanger in order to reduce the load on the primary, in-tank heat exchanger.

Capital and annual operating costs of this system are listed on the enclosed worksheets and are summarized on a Capital Expenditures and Materials Requirements Summary Reporting Form. All annual cost figures are averaged over the lifetime of the system. It should be noted on the Capital Requirements worksheets that the harvesting ship alone represents 51.5 percent of the total materials and equipment costs which are \$310,165 per 10^{10} Btu of annual output capacity. The harvesting capital costs are \$328,850 per 10^{10} Btu of annual output capacity, and there are no production (kelp growing) costs. Construction labor overhead and profit for the shore based facilities represent 41.6 percent of the total capital costs, or \$478,500 per 10^{10} Btu of annual output capacity. More detail on this capital cost breakdown is contained in a subsequent paragraph of this section.

CAPITAL EXPENDITURES AND MATERIALS REQUIREMENTS SUMMARY REPORTING FORM

TECHNOLOGY Marine Biomass
APPLICATION Natural Bed Kelp System
DATE SUBMITTED 20 October 73
SUBMITTED BY LBL

REGIONAL APPLICABILITY OF DATA:
NATIONAL: ______
FEDERAL REGION NOS. ______
STATES: California, Oregon, Washington

A. CAPITAL COSTS	$1977 x 10^3	DEFLATOR	$1972 x 10^3
1. MATERIALS	2914.3	1.43	2038.0
2. TRANSPORTATION	142.6	1.43	99.7
3. CONSTRUCTION LABOR	1456.0	1.43	1018.2
4. PROFIT & OVERHEAD	728.0	1.43	509.1
A.1 TOTAL	5240.9	1.43	3665.0

B. ANNUAL SYSTEM 10^{12} BTU OUTPUT 0.0456(10^{12}BTU/yr)

C. ANNUAL SYSTEM FOSSIL FUEL EQUIVALENT/10^{12} BTU OUTPUT 0.0456(10^{12}BTU/yr)

D. TOTAL CAPITAL COST/10^{12} ANNUAL BTU $\left[\frac{A.1}{B}\right]$ \$80,372,800 /10^{12}BTU

E. NUMBER OF YEARS TO CONSTRUCT FACILITY 1

F. PHASING OF CONSTRUCTION COSTS ($ EACH YEAR):

YEAR	1	2	3	4	5	6	7	8	9	10
%	100	—	—	—	—	—	—	—	—	—

G. EXPECTED LIFE OF FACILITY (YEARS) 40

H. MAN YEARS TO CONSTRUCT FACILITY 51 man years

I. MAN YEARS/10^{12} BTU ANNUAL OUTPUT $\left[\frac{H}{B}\right]$ 1336.5man years

J. ESTIMATED LAND USE 18 acres/plant
(∿ 395 acres/10^{12} BTU/yr)

K. ESTIMATED WATER USE ∿1.8×10^5 gal/10^{12}BTU

1 of 3

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Marine Biomass APPLICATION: Natural Bed Kelp System DATE: 19 October 78

Expenditures			(4) Total Cost 1977$x10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			186.2	2432	Plywood	45	0.16			1
			21.9	2431	Millwork & Wood	46	0.02			1
			3177.4	3271 3272	Cement, Concrete	89	2.77			0
			160.0	321 3293	Stone,Glass,Clay	90	0.14			0
			2222.6	3339	Steel	91	1.94			1
			2909.7	3334	Aluminum	95	2.53			1
			98.6	3339	Other Primary Metal	96	0.09			1
			375.1	3433	Plumbing & Heating Equipment	102	0.33			1
			664.3	3443	Boiler Shops	103	0.58			0
			46.0	3480	Misc. Fabricated Wire	108	0.04			1
			65.7	2821	Plastic Material	68	0.06			0
			38.3	2950	Paving &(asphalt)	78	0.03			0
			4114.7	3352 3356 3361	Fabricated Struc. Products	104	3.58			1
			449.2		Non-celluloise Fiber	71	0.39			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Marine Biomass APPLICATION: Natural Bed Kelp System DATE: 19 October 78

Expenditures			(4) Total Cost 1977$x10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			1187.5	3494 3498	Pipes,valves, fittings	109	1.03			1
			3597.6	3499 3491 3399	Fabricated steel Products	110	3.13			1
			229.9	3535	Material Handling Equipment	114	0.20			0
			1407.7	3565 3559 3567	Special Indus. Equipment	118	1.23			0
			1209.4	3511	Engines & Turbines	111	1.05			1
			652.0	3564	Pumps,Compressions Blowers	119	0.57			1
			104.1	3566	Power Transmission Equipment	121	0.09			1
			328.7	3611	Electrical Measure	129	0.29			1
			394.4	3612 3613	Transformers Switches	130	0.34			1
			2093.5	3621	Motors,Generators	131	1.82			1
			208.1	3622	Industrial Control Equipment	132	0.18			1

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Marine Biomass APPLICATION: Natural Bed Kelp System DATE: 19 October 78

Expenditures			(4) Total Cost 1977$10^3	Inforum Sector Designation			(8) Fraction of Total Cost^d(%)	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category^a	(2) Quantity & Units	(3) Price^b		(5) SIC#^{c}	(6) SEAS SECTOR	(7) SEAS #				
Harvesting System			87.8	3640	Electrical wiring	135	0.08			1
			547.8	399	Misc. Manufacture	166	0.48			0
			843.5	2431	Millwork & Wood	46	0.73			0
			624.6	3271 3272	Cement & Concrete	89	0.54			0
			510.1	3441 3399	Steel	91	0.44			1
			2432.0	3536	Material Handling Equipment	114	2.12			1
			32,865	3731	Ship Building	150	28.63			1
Total Material & Equipment			63,853.4				(55.61)			
			3124.0	-----	Transportation	169	2.72			0
Labor (2.63x10^{6}hrs@(12.15/hr)			31,900	-----	New Construction	19	27.78			0
Overhead	(wages)		9,570	-----	New Construction	19	8.33			0
Overhead	(other)		3,190	-----	New Construction	19	2.78			0
Profit (10%)			3,190	-----	New Construction	19	2.78			0
TOTAL COST			114,827.4				100.00			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

1 of 2

TECHNOLOGY CAPITAL COSTS: WORK SHEET /ANNUAL COST

TECHNOLOGY: Marine Biomass APPLICATION: Natural Bed Kelp System DATE: 19 October 1978

Expenditures			(4) Total Cost 1977\$X10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			510.2	2990	Petroleum Prod.	76	1.72			0
			6351.6	2810	Industrial Chem.	64	21.40			0
			95.0	3494	Piping & fillings	109	0.32			1
			1.6	2850	Paint,finishes	74	0.01			0
			3.3	2821	Plastic Material	68	0.01			0
			288.0	3352 3356 3361	Fabricated Structural Material	104	0.97			1
			251.8	3499 3399	Fabricated Metal Products	110	0.85			1
			56.3	3565 3559	Special Indus. Equipment	118	0.19			1
			104.7	3621	Motors, Generators	131	0.35			1
			9.2	3535	Material Handling Equipment	114	0.03			1
			8.3	3566	Power Transmission	121	0.03			0
			11.8	-----	Misc. Material	-----	0.04			
			19.7	3612	Transformers & Switches	130	0.07			0
	Total Material		7711.5				(25.98)			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET /Annual Cost

TECHNOLOGY: Marine Biomass APPLICATION: Natural Bed Kelp System DATE: 19 October 1978

Expenditures			(4) Total Cost 1977\$X10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			585.9	-----	Trucking	169	1.97			0
Labor(1.358x10^6hrs@10.50)			14,263.0	-----	Maintenance Const.	20	48.04			0
Overhead	(wages)		4,279.0	-----	Maintenance Const.	20	14.41			0
Overhead	(other)		1,426.0	-----	Maintenance Const.	20	4.80			0
Profit			1,426.0	-----	Maintenance Const.	20	4.80			0
	TOTAL COST		29,692.5				100.00			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

OCEANIC FARM SYSTEM

Introduction

The oceanic farm system employs a 10.5 square mile open ocean farm supported on a support framework anchored in several thousand feet of water and maintained at a depth of 80 feet to 100 feet. Enhanced kelp growth is supported by a series of upwelling pipe and pumps which pump nutrient rich water up to the kelp from a depth of 500 feet - 800 feet. The farm is assumed to be sited 100 miles off shore. As described earlier in this report, average yield for the farm is 50 tons (DAF) per acre-year. Thus total annual production from the farm is 3.62×10^6 tons of wet kelp.

The shore based conversion plant for this system is designed to process 1000 tons (DAF) per day (14,285 wet tons per day) for a 260 day operational year. Schematically this plant is identical to 300 ton per day natural kelp bed system plant.

Two harvesting concepts were considered. In the first, the harvest ship shreds the kelp, adds calcium chloride to the slurry, and stores the slurry in the hold for transport to shore. In the second, the harvest ship shreds and grinds the kelp, performs on board calcium chloride treatment and presses the kelp to cake form. The brine from this pressing operation is then returned to the kelp bed as a nutrient source. The advantage of the second system is that it reduces the mass flow rate of kelp between the farm and shore and thus substantially reduces both required ship capacity and annual ship travel costs. The disadvantages of the second system are that the brine flow is lost to the processing system, and that the complexity of the ships cargo handling capability is substantially increased. In order to maintain sufficient sludge flow into the fluidized bed combuster to support plant energy requirements, the first harvesting system was selected for this system design.

The farm size selected for this system (10.56 mi^2) is considerably smaller than that assessed in previous major kelp conversion studies (e.g. Intergrated Sciences, Inc., 1978, and Dynatech, 1978) which assessed farms as large as 100,000 acres, or than proposed future major farms which are projected to be in the thousands of square miles size range (Bryce, 1978). This size reduction was based on a cursory review of the potential structural, mooring, institutional, international, and capital problems associated with that scale. In order to provide some concept of the magnitude of these problems, limited summary information on two of those areas is included here. First, the total cost of labor associated with the creation and maintenance of a large ocean farm has not been adequately assessed. A quick check of the number of individual kelp plants to be implanted at a depth of 100 feet at the farm, and of potential diver operation indicates that more than 1300 man years of diver time will be required to initially attach the kelp field assuming near optimal diver efficiency, coordination and weather condition. The cost of this kelp attachment operation alone will add approximately one hundred million dollars to the capital cost of the operation. Further, over 250 divers would be required for permanent duty to locate and replace missing plants, which either break free during storm or otherwise require replacement. Similarly, based on the structure material life expectancy, on pump and generator requirement, and on the forces to which the structure will be subjected, an on-site work force of between 500 and 900 persons will be required to repair and maintain the support structure and the upwelling pumps and generators. The logistics and costs of maintaining a permanent on-site work force of 800 to 1200 persons have not been adequately accounted in previous cost estimates.

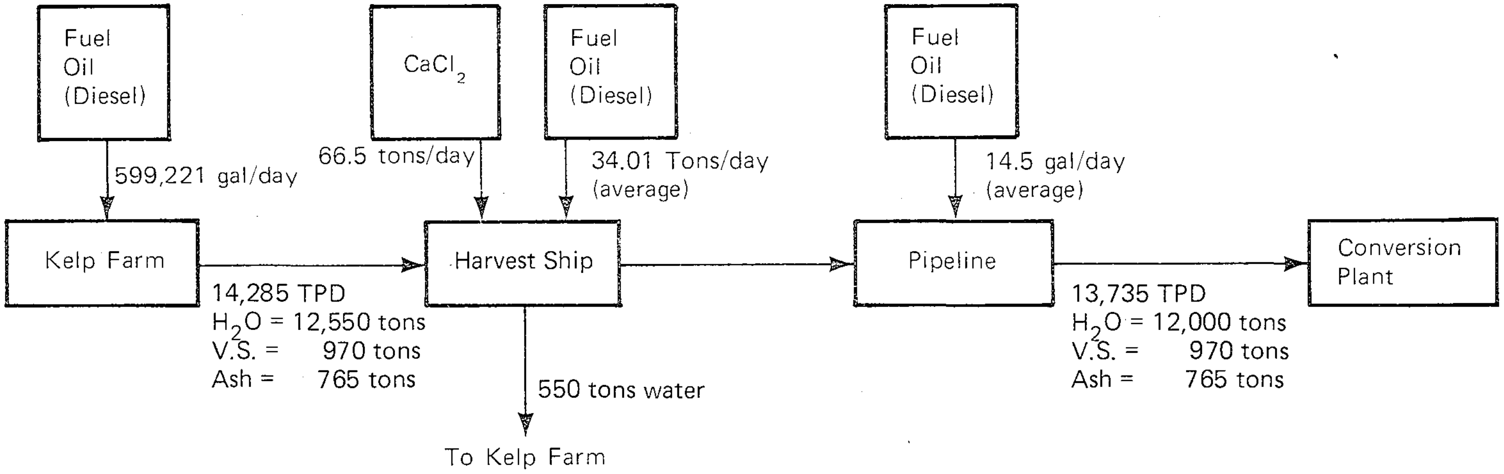
Second, analyses associated with ocean thermal energy conversion (OTEC) operations (Debok and Haffen, 1974, DOE, 1978) indicate that the two greatest problems confronting deep ocean mooring are 1) designing the mooring line to withstand the drag force exerted on the line itself and to withstand the forces of its own weight, and 2) designing an anchoring system capable of holding under tremendous lateral forces. While mooring requirements have been dealt with lightly in previous kelp work, it is felt that maintaining the position of a submerged 156 mi^2

structure would be a major problem whose solution would add significantly to the total capital cost. Dynamic positioning systems were rejected as the large amount of energy thus consumed would seriously reduce net system output.

Basic material flows from the kelp farm into the onshore processing plant are shown on Figure 10. Processing flows within the conversion facility are proportional to those described in Figure 8 for the natural kelp bed system. Listed fuel oil inputs support QAM diesel generators, harvest ship and pipeline pump station operation. A brief description of the major elements within the ocean farm system is given below.

Support Structure

The support structure is based on an assemblage of quarter acre modules (QAM) as described by Bryce (1978) and by James and Murphy (1976). The structure uses a high density polyurethane deep ocean water pipe with a 24 inch diameter and uses three 20 horsepower pumps per QAM supported by a 65Kw diesel generator to provide pumping and auxiliary power. The central cylinder is encased in steel and the main support ribs are steel. Other lines are high density polyurethane. Three 4000 feet anchor lines are used to moor each QAM within the farm. The total farm is 3.25 miles on each side and contains 27,040 QAM's. Substantial uncertainty exists both for the structural integrity of the farm's platform under various storm loads, and for the capacity of the mooring and anchoring system to withstand both current and storm forces. A platform system designed to withstand a 30 year or 50 year storm may easily cost far more than can be justified by the products of the farm. For the QAM system, a yield of 50 tons (DAF) per acre-year at 8000 Btu/lb is assumed for these calculations in order to maintain a comparable analytical base with previous major assessments (Wilcox, 1975). Thus, farm production is 4,828,600 wet tons per year.



XBL 781-13497

Fig. 10. Operational Material Flows for the Ocean Farm Kelp Conversion System

Harvest System

One 30,000 DWT ship with a total crew of 38 is required to harvest kelp from the 10.56 mi^2 farm. The ship costs $36,510,000 and will be powered by a 12,800 shaft horsepower engine. The ship will cut kelp at a depth of 10 feet from a rear mounted blade structure, will convey the kelp through shredders, and mix calcium chloride with the resulting kelp slurry at 0.5% concentration factor, and store the slurry in the ship's hold. Approximately 4% of the kelp water content will be lost during shredding and will be returned to the farm. Harvest operation (at a speed of 3 knots) will require approximately 16 hours. Transit time to and from shore will require approximately 12.5 hours, and approximately 3.5 hours will be required to pump the kelp slurry out of the hold at the off-shore buoy terminal. Total trip time will be approximately 33 hours. One trip will be required every two days in order to maintain a 1000 TPD (DAF) flow rate into the plant. This flow rate also will insure total farm harvest in 180 harvest trips. Annual ship fuel consumption will be 12,243.5 tons of diesel oil, annual labor cost will be $1,452,679, and non-labor annual operation cost will be $202,000.

The off-shore terminal facility will be a single point moored buoy with a pipeline onto shore. It is assumed that the total pipeline distance to the conversion plant is 10 miles and that one mid span pumping station will be required to maintain the slurry flow. Pipe diameter will be three feet and slurry velocity will be maintained at 8 fps during off-load operation.

Processing Plant

The components and operation of the conversion plant will be identical to that of the natural bed system, however, the input flow rate will be increased by a factor 47.3. Total oceanic system output is 2.16×10^{12} Btu/year.

Detailed capital costs for an annual system output capacity of 10^{12} BTU/year are shown on the attached worksheets and Capital Requirements Summary Reporting Form. Total cost for the system as described is $1.977 billion. A breakdown of this cost into its major components and a comparison of this system with the natural bed kelp conversion system are contained in the next paragraph of this section. These cost estimates are based on a set of conservation assumptions concerning component performance. It is probable that actual capital and operating costs could be held below the level shown here. This is accentuated by the assumption made in these calculations that all components are costed at the single item retail price. Thus, the costs presented in this report represent an upper bound on actual costs.

CAPITAL EXPENDITURES AND MATERIALS REQUIREMENTS
SUMMARY REPORTING FORM

TECHNOLOGY Marine Biomass
APPLICATION Ocean Farm Kelp Bed
DATE SUBMITTED 19 October 1978
SUBMITTED BY LBL

REGIONAL APPLICABILITY OF DATA:
NATIONAL:
FEDERAL REGION NOS.
STATES: California, Oregon, Washington

		$1977x10^3$	DEFLATOR	$1972x10^3$
A.	CAPITAL COSTS	\$1977x10³	DEFLATOR	\$1972x10³
1.	MATERIALS	814,660.6	1.43	569,692.7
2.	TRANSPORTATION	135,380.8	1.43	94,671.9
3.	CONSTRUCTION LABOR	684,656.7	1.43	478,780.9
4.	PROFIT & OVERHEAD	342,328.3	1.43	239,390.4
A.1	TOTAL	1,977,025.6	1.43	1,382,535.9

B.	ANNUAL SYSTEM 10^{12} BTU OUTPUT	$2.16(10^{12}$BTU/year)
C.	ANNUAL SYSTEM FOSSIL FUEL EQUIVALENT/10^{12} BTU OUTPUT	$2.16(10^{12}$BTU/year)
D.	TOTAL CAPITAL COST/10^{12} ANNUAL BTU $\left[\frac{A.1}{B}\right]$	\$640,062,000/10^{12}BTU
E.	NUMBER OF YEARS TO CONSTRUCT FACILITY	4

F. PHASING OF CONSTRUCTION COSTS ($ EACH YEAR):

YEAR	1	2	3	4	5	6	7	8	9	10
%	20	20	20	20						

G.	EXPECTED LIFE OF FACILITY (YEARS)	35
H.	MAN YEARS TO CONSTRUCT FACILITY	1.72×10^{14}man years
I.	MAN YEARS/10^{12} BTU ANNUAL OUTPUT $\left[\frac{H}{B}\right]$	7.966×10^{3}man years
J.	ESTIMATED LAND USE	5.35×10^{2}acres
	WATER USE:	6,760 acres

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Marine Biomass

APPLICATION: Oceanic Farm Kelp System

DATE: 19 October 1978

Expenditures			(4) Total Cost 1977\$x10^{3}	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
Oceanic Farm Subsystem										
			29,913.0	2821	Plastic Material	68	2.94	Equal to one for all cost items		0
			35,031.0	3399	Steel	96	3.83			1
			11,111.6	2824	Non cellulose fiber	71	1.21			0
			4,296.1	3611	Electronic Meas. devices	129	0.97			1
			2,512.5	3622	Indus. Controls	132	0.27			1
			1,378.3	321 3293	Stone,Clay Glass	90	0.15			0
			231.9	3612	Transformers,	130	0.03			1
			174.1	3480	Misc. Fab. Wire	108	0.02			0
			42,288.7	3621	Motors, Generators	131	5.28			1
			29,399.2	3564	Pumps,Compressors	119	3.21			1
			20,534.6	3352 3356 3361	Fabricated Struc. Prod.	104	2.24			1
			3,086.2	3498 3494	Pipes,valves, Fittings	109	0.34			1
			7,625.2	3691	Batteries	140	0.83			0
			137,967.9	2824	Non-cellulose	70	15.08			0
	Subsystem Total		328,550.4				(35.90)			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

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TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Marine Biomass APPLICATION: Oceanic Farm Kely System DATE: 19 October 1978

Expenditures (1) Category^a	(2) Quantity & Units	(3) Price^b	(4) Total Cost 1977 $x10^3	Inforum Sector Designation (5) SIC#^c	(6) SEAS SECTOR	(7) SEAS #	(8) Fraction of Total Cost^d	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle^1
Harvesting Subsystem										
			16,903.4	3730	Ship & Boat Build.	150	1.85			1
			184.0	3271 3272	Cement & Concrete	89	0.01			0
			83.3	2431	Millwork & wood	46	0.01			0
			324.0	3339	Steel	91	0.04			1
			30.2	3621	Mootors&generators	131	0.003			1
			120.0	3494 3498	Pipes, valves, Fittings	109	0.01			1
			5.1	3564	Pumps,compressors	119	0.001			1
			4.2	3334	Aluminiun	95	0.0002			1
			285.7	3499	Fabricated metal products	110	0.03			1
			40.4	335	Misc. structural	104	0.002			0
			4,086.0	2821	Plastic Materials	68	0.45			0
	Subsystem Total		22,066.4				(2.41)			
Processing Subsystem										
			187.9	2432	Plywood	45	0.02			1
			14.7	2431	Millwork & wood	46	0.002			0
			2,827.0	3271 3272	Cement, concrete	89	0.31			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Marine Biomass APPLICATION: Oceanic Farm Kelp System DATE: 19 October 1978

Expenditures			(4) Total Cost 1977 $\$ \times 10^3$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			91.6	321 3293	Stone, Clay,Glass	90	0.01			0
			2,236.6	3339	Steel	91	0.24			1
			2,927.9	3334	Aluminium	95	0.32			1
			99.3	3339	Other Primary Metals	96	0.01			1
			423.8	3433	Plumbing&Heating Equipment	102	0.05			1
			677.7	3443	Boiler Shop	103	0.07			1
			74.1	3480	Misc. Fab. Wire	108	0.01			1
			111.7	2821	Plastic Material	68	0.01			0
			24.7	2950	Paving & Asphalt	78	0.005			0
			4,140.5	3352 3356 3361	Fabricated Structural Products	104	0.45			1
			424.3	2824	Non-celluloise Fiber	71	0.05			0
			2,259.7	3494 3498	Pipes,valves, Fittings	109	0.25			1
			3,573.8	3499 3399	Fabricated Metal Products	110	0.39			1
			106.5	3535	Material Handling Equipment	114	0.01			1

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Marine Biomass
APPLICATION: Oceanic Farm Kelp System
DATE: 19 October 1978

Expenditures			(4) Total Cost $1977\$\times10^3$	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			1,370.3	3565 3559 3567	Special Indus. Equipment	118	0.15			1
			985.5	3511	Engines & Turbines	111	0.11			1
			758.0	3564	Pumps, Compressors Blowers	119	0.08			1
			104.7	3566	Power Transmission Equipment	121	0.01			1
			191.9	3611	Electrical Meas. Equipment	129	0.02			1
			304.2	3612 3613	Transformers, Switches	130	0.03			1
			1,921.5	3621	Motors, Generators	131	0.21			1
			209.4	3622	Industrial Control Equipment	132	0.02			1
			102.2	3640	Elec. Wiring	135	0.01			0
			551.2	399	Misc. Manufact.	166	0.06			0
	Subsystem Total		26,700.6				(2.92)			
Total Material and Equipment			377,157.7				(41.22)			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

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TECHNOLOGY CAPITAL COSTS: WORK SHEET

TECHNOLOGY: Marine Biomass APPLICATION: Oceanic Farm Kelp System DATE: 19 October 1978

Expenditures			(4) Total Cost 1977$ 10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			46,248.8	4200	Trucking	169	5.05			0
			16,427.5	4400	Water Transportation	170	1.79			0
Labor(Oceanic Farm Subsystem 1.397x10^7hrs at $12.5)			278,731.0	----	New Construction	19	30.45			0
Labor (Harvest Subsystem 3.0597x10^5hrs at $12.5)			6,104.7	----	New Construction	19	0.67			0
Labor (Process Subsystem 1.657x10^6hrs at $12.15)			32,135.0	----	New Construction	19	3.51			0
Overhead (wages)			95,091.3	----	New Construction	19	10.39			0
Overhead (other)			31,697.0	----	New Construction	19	3.46			0
Profit (10%)			31,697.0	----	New Construction	19	3.46			0
	TOTAL COST		915,290.2				100.00			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

1 of 2

TECHNOLOGY CAPITAL COSTS: WORK SHEET / ANNUAL COSTS

TECHNOLOGY: Marine Biomass APPLICATION: Ocean Farm Kelp Bed DATE: 19 October 1978

Expenditures			(4) Total Cost 1977$x10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d]	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			875.1	2990	Petroleum Refining	76	0.72	Equal to one for all components		0
			43,520.6	2911	Fuel Oil	77	35.38			0
			2,245.7	3399	Steel	91	1.85			1
			3,399.6	2821	Plastic Material	68	2.80			0
			89.4	321	Stone,Clay Glass	90	0.07			1
			19.1	3480	Misc. Fab. Wire	108	0.02			1
			3,480.2	3621	Motors&Generators	131	2.87			1
			24,362.0	2810	Industrial Chem.	64	20.06			0
			1,500.2	3564	Pumps,Compressors	119	1.24			1
			1,228.0	335	Fab. Structural	104	1.01			1
			508.3	3691	Batteries	140	0.42			0
			118.4	264	Paper Products	52	0.10			0
			83.1	2850	Paints	74	0.07			0
			76.1	2890	Cleaning Products	73	0.06			0
			810.8	349	Pipes,valves, Fittings	109	0.10			1
			124.1	3499	Fab. Metal Prod.	110	0.10			1
			78.5	399	Misc. manufact.	168	0.06			1
			94.1	3559 356	Special Indus. Equipment	118	0.08			1
			68.4	3511	Engines,Turbines	111	0.06			1
			19,556.6		Non celluloise Fib.	70	16.10			0

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

2 of 2

TECHNOLOGY CAPITAL COSTS: WORK SHEET/ANNUAL COSTS

TECHNOLOGY: Marine Biomass

APPLICATION: Ocean Farm Kelp Bed

DATE: 19 October 1978

Expenditures			(4) Total Cost 1977\$x10^3	Inforum Sector Designation			(8) Fraction of Total Cost[d] (%)	(9) Scale Factors And Year Applicable	(10) Footnotes	(11) Recycle[1]
(1) Category[a]	(2) Quantity & Units	(3) Price[b]		(5) SIC#[c]	(6) SEAS SECTOR	(7) SEAS #				
			81.8	3588	Power Transmission Equipment	121	0.05			1
			119.3	3640	Misc. wiring	135	0.10			1
Total	Material&Equipment		102,419.4				(84.32)			
			2,575.9	4200	Trucking	169	2.12			0
			3,512.6	4400	Shipping	170	2.89			0
Labor (7	.02x10^{5}hrs@1	2.3(avg.))	8,634.6	----	Maint. Construc.	20	7.11			0
			2,590.4	----	Maint. Construc.	20	2.13			0
			863.5	----	Maint. Construc.	20	0.71			0
			863.5	----	Maint. Construc.	20	0.71			0
Total	Annual Cost		121,459.8				100.00			

(a) For construction category, indicate the number of man-hours of labor required. (b) Prices should be for 1972. If other prices are used, indicate year. (c) 1967 SIC code. (d) Numbers may not add to totals due to rounding.

[1] 1 = yes, 2 = no. Those items not recycled become land residuals, quantities of recycled materials per 10^{12} annual Btu output are contained in the list of side equations.

SYSTEM COST COMPARISON

A comparison of various components of the capital and annual costs of the natural bed supported kelp conversion system and the oceanic farm supported kelp conversion system is shown on Table 7. The first column under both Material/Equipment and Labor/Overhead sections on that table lists the required cost (in 1977 $), to construct 10^{10} Btu's worth of prototype system described in this report. Thus, the column is a "normalized" cost column to allow comparison of the systems on a cost-per-unit-output basis. As can be seen, the capital costs of the ocean farm kelp production subsystem dominate all capital cost components. It should also be noted in the first column of each section that economies of scale are realized in the large scale harvest system so that the harvest unit cost for the oceanic farm system is significantly lower than for the natural bed system. The cost of processing is closely tied to throughput rates and thus unit processing costs show little change with the scale of operation. Normalized natural bed annual labor costs are high because plant output is small and a large number of separate plants are required to produce comparable total output. Total capital and annual unit cost for the ocean farm system are higher than for the natural bed system by factors of 9 and 4.3 respectively.

The second column of both the Material/Equipment section and the Labor/Overhead section shows the percent of total costs represented by the Production, Harvest and Process subsytems. Additionally, two specific large components, the harvest ship for the natural bed system and the anchor lines for the oceanic system, are shown as separate line items as well as being a portion of one of the major cost categories.

The third column in each section of Table 7 list the total component cost for the prototype systems described in the report. The final column of the table list total (materials plus labor) prototype component and system cost. Thus, the total capital cost of the natural kelp bed system (less transportation costs) is $5.1 million with annual costs of $1.3 million, 75 percent of which is labor costs. The

Table 7

Kelp Conversion System Cost Comparison

Cost Category	Material/Equipment $/10^10 BTU	%	Prototype System ($10^3)	Labor/Overhead $/10^10 BTU	%	Prototype System ($10^3)	Prototype Total ($10^3)
A. Capitol Costs							
1. Natural Bed							
● Production	0	0	0	0	0	0	0
● Harvest	372,752	58.4	1,701.3	90,915	19.1	414.9	2,116.2
(ship alone)	(328,650)	(51.5)	(1,500.0)	-----	-----	----	-- --
● Process	265,782	41.6	1,213.0	387,585	80.9	1,769.0	2,982.1
TOTAL	638,534	100.0	2,914.4	478,500	100.0	2,183.9	5,098.3
2. Ocean Farm							
● Production	3,285,504	87.0	709,668.9	4,180,965	88.0	903,088.4	1,612,757.3
(Anchor Line alone)	(1,516,401)	(40.2)	(327,542.6)	----	-----	----	----
● Harvest	220,664	5.9	47,663.4	91,571	1.9	19,779.3	67,442.7
● Process	267,006	7.1	57,673.3	482,025	10.1	104,117.4	161,800.7
TOTAL	3,771,577	100.0	814,660.6	4,754,560	100.0	1,026,985.0	1,841,645.6
B. Annual Costs							
1. Natural Bed	77,115	100.	351.6	214,450	100.	977.9	1,329.5
● Fuel alone	(5,102.)	(6.6)	(23.2)	----	-----	----	
2. Ocean Farm	1,024,294	100.	2,212,247.5	129,520	100.	279,763.2	501,010.7
● Fuel alone	(580,237)	(56.6)	125,331.2	----	-----	----	

ocean farm system will cost $1.84 billion to construct (not including transportation), 87.5 percent of which is associated with building the kelp support structure and upwelling system. Annual costs for that system will be as high as $500 million with the two major components of that figure being maintenance labor for the kelp farm and diesel fuel to power the upwelling system.

Three conclusions are apparent from the data presented in Table 7. First, the ocean farm concept is not an economically viable concept using present farm designs. Second, some economics of scale should be realized for a natural bed system if total kelp throughout were increased from 300 wet tons per day to 1000 to 2000 wet tons per day. These economies should be realized for four reasons. First, as described earlier in this report, 1000 TPD to 2000 TPD harvest rate can be realized from a relatively small (2 mi^2 to 4 mi^2) coastal kelp bed. Second, larger product flow rates would more fully utilize the processing plant. Third, the increased flow rate would not require proportional increases in operational labor. Finally, large harvest rates would not require a proportional increase in the capital cost of a harvest ship. However, even when operating at maximum economic efficiency, a natural kelp bed system producing energy products only will be marginally economic at best. Third, neither system is economically attractive solely as an energy producer based on current methane prices. The profitability of a kelp to methane conversion system will depend to a large extent on the production and sale of by-products to the methane production process such as algin, livestock feeds, or fertilizers. The following paragraphs describe the most attractive of these byproducts, alginic acid, and briefly describe the concept of a multiple product processing plant.

Multiple Product Recovery Processing Plant

The methane generation process previously described in the paper converted only 40 percent of the available volatile solids into methane. The remainder were used as a source of energy to drive the plant. Increased production rates from this level are possible. The recovery rate could have been increased by recycling sludges and juices into the digester. Such a process would require that processing energy be purchased rather than produced internally and would produce only a 5% to 10% increase in methane production. Alternately, it would be possible to suboptimize the digester for methane production and to then recover alginic acid from the digester as a simultaneously generated byproduct. This process would reduce methane yields but would generate significant quantities of a valuable byproduct ($2.00 to $3.00 per lb.) on the current market. In addition, recent development indicate that processes using multiple digesters in series may increase methane yields to as high as 65-70% (Ghosh, et al., 1978) and still could allow algin recovery operations.

Within this section, first the most attractive byproduct, alginic acid and the history of its production from kelp are briefly described. Following this brief discussion, conceptual descriptions of the conversion processes to produce alginic acid as a byproduct to methane and to enhance methane production rates are given.

Although Krefting is credited with the first purification of alginic acid in 1896, it was not until 1964 when partial acid hydrolysis studies showed that a significant percentage of alginic acid molecules contained both mannuronic and guluronic acid. While this M/G ratio was subsequently shown to vary depending on the specific seaweed from which it was extracted, Macrocystis pyrfera appears to consistently range about 1.56. This compares favorably with the brown algae Ascophyllum nodosum, which has a variable M/G ratio of from 1.1 to 1.85. For the six algae for which data are available, the average M/G ratio is 1.33. Additional studies via p.m.r. spectroscopy determined that these differences were related to molecular bonding angles in the glycosidic linkages in polymannuronic and polyguluronic acid chains.

These differences in structure are now understood to account for differences in physical properties and end use utility of alginic acid isolated from different species of kelp. Specifically it appears to influence the ability of alginic acid to form gels of specific syneresis characteristics when reacted with calcium salts. These gels, which have structural properties, consist of about 99% water and 1 - .5% alginate.

Macrocystis pyrifera tends to form a deformable elastic gel with significant water rentention properties. Because algin is a hydrophilic colloid, gel-like precipitation can also be accomplished by the addition of non-aqueous water miscible solvents such as alcohols or acetone to an aqueous solution. In this case the result is a viscosity increase of the water bound algin which has a specific precipitation point for each grade of algin with respect to specific solvent concentrations. Viscosity of algin is also proportional to ph, the exact maximum tolerance again related to the percent composition and grade of the feedstock.

The nine active solvents and average maximum tolerance are Methanol 28%, Ethanol 23%, Isopropanol 19%, + - Butanol 23%, Glycerol 67%, Ethylene Glycol 70%, Propylene Glycol 52%, Butyl Cellosolve 30%, Acetone 17%.

As Uziel et al., (1975) and Babbitt (1968) have identified many of the above as present in anaerobic digesters during methane formation, and since acid formation is a limiting factor in the process, it is possible to form an alginaic gel directly in the reactor thus adding significantly to the end use value of the kelp.

The economic impact of this by product addition to the described 300 wet ton per day processing plant are very significant. Through the addition of hydroxides to control pH a gel of several types of sodium alginate is produced. Once isolated, these alginates retail for $2.00 to $3.00 per pound (1978). Thus daily production of between 500 lb and 600 lb of sodium alginate (equivalent in moss to less than 0.1% of the daily kelp inflow rate) could generate $500,000 in increased plant annual revenue without significantly decreasing methane production.

Additionally, recent analysis indicated that a series digester system with heat treatment could substantially increase methane production rates and still permit alginic acid recovery. McCarty, et al (1978), has investigated the use of heat treatment on wastes with temperatures ranging from 75°- 250°C and ph 1-13 with a detention time of up to 3 hours. Assuming subsequent fermentation is allowed to proceed at 35°C, a 73% increase volatile solids reduction and CH_4 production has been achieved over that for which heat treatment was not used.

In a two stage processing system optimized to extract alginic acid and CH_4 would work along the following lines. Kelp is harvested, washed and milled to uniform size then fed to a pre-digester where gas is extracted and the ph held at 4. The partly digested sludge is then removed to the heat treatment process where temperatures of 200°C are reached. Alkali is added to raise the ph to 13 and the result is a viscus percipitate gel rich in alginic acid. The gel is removed for refining while the remaining sludge is fed to the main digester where the remaining available gas is extracted. Residual sludge heat should be sufficient to maintain the secondary digester temperature at 35°C.

VII. ENVIRONMENTAL RESIDUALS

This section provides data on the generation of environmental residuals from an ocean biomass system that converts marine algae to methane gas. Since there are no full scale systems in operation, the residuals information represents a compilation of potential impacts from bench-scale experiments of the conversion system and the conceptual schemes of the production, harvesting and processing components. Data for the expected generation rates of operational residuals are listed in a format for use as input to the SEAS model. A brief description of the potential environmental impacts is given below.

The impacts of a massive open ocean farm operation have not been explored. There is a potential for significant climatic modifications, since the culture and harvesting of seaweeds over several thousand square miles of the ocean surface will result in changes in albedo, air-sea exchanges of materials, and altered surface roughness. The farm structures themselves will reduce or change the patterns of water circulation. These factors which could change prevailing weather patterns and create additional fog banks subsequently may have some effect on the productivity of the kelp beds.

Another potential problem associated with the farm structures of a sea farm system is the release of numerous chemicals into the ocean from the supports and synthetic lines used to hold the algae. Hruby (1978) noted that possible slow release of toxic metals from the anti-fouling paints and organic chemicals leached from the nylon lines. The degree of concern regarding these chemicals is unknown at this time. Dissolved organic chemicals such as phenols will be released by the marine kelp. Sieburth (1969) estimated that these organic compounds could be exuded by the algae at rates as high as 40 percent of the net carbon fixed. Calculations based on available data suggest that the release of extracellular organic compounds by *Macrocystis* will be a problem (Hruby, 1978). The exudations from brown algae have been found to be toxic to some marine organisms.

The upwelling system which is designed to provide an abundance of nutrient-rich water needed for kelp growth and development could present several environmental problems. The temperature differences between upwelled waters and those present on the ocean's surface might form large fog banks as warm moist air is blown over the cooler deep water. One consequence of such fog banks is to reduce the amount of sunlight reaching the surface which, in turn, could affect the rate of productivity.

The upwelling of water may alter salinity, temperature, dissolved oxygen, turbidity and nutrient levels. While artificial upwelling may support increased biological production in the kelp beds, it may also increase the growth of less desirable planktonic species which may have long term effects on the residential biological communities.

Furthermore, the upwelling of deep water will entrain marine organisms which cannot resist the vertical inflow velocities. Organisms that are entrained will be subject to mechanical pressure and sheer stresses. The survival rate of mesopelagic organisms in the upwelling streams is species-specific.

A final problem with the upwelling system is related to the use of diesel-powered pumps. There are several possible air pollutants (e.g. particulate, NO_x and hydrocarbons) that would be emitted to the atmosphere from the pumping operations. The level of emissions corresponds to the type of system selected.

Another problem associated with the production aspects of the marine biomass farm is the accumulation and toxicity resulting from heavy metals such as cadmium, chromium, cobalt, copper, lead, and mercury. This impact will occur if nutrients are provided by recycling the fermentation wastes or by using sewage sludge effluents. Since algae concentrate heavy metals present in seawater by factors ranging from 40-100,000 (Goldberg, 1965), it can be expected that plants associated with a marine biomass farm will absorb the metals present in the seawater as well as any present in residues used as nutrient supplements.

Algal farms, depending on their size and location, may have a negative impact on commercial shipping if they disrupt existing shipping lanes. Furthermore, such large marine biomass farms may adversely affect access to and utilization of coastal fishing locations. Several institutional and legal issues are likely to accompany the research, development, and commercial phases of the open ocean system if they are located beyond 12 mile or 200 mile limits. Not only will international and domestic legal status have to be analyzed, but a regulatory framework will have to be established to guarantee the various uses of marine resources. Figure 11 (Knight, 1976) outlines the basic zones of ocean jurisdiction which must be taken into consideration in any discussion of offshore marine biomass farms.

The harvesting aspect of the marine biomass system involves the use of ships with the Kelco Company design. The harvest ships will create some environmental impact due to the emissions during their normal operations. The Kelco ships burn diesel as a fuel source which results in the production of particulates, nitrogren oxides, and hydrocarbons as primary air pollutants. These pollutants, however, will be generated over a more widespread area, since they are released as the ships travel to and from the offshore kelp farm. In addition to the air emissions there may be liquid effluents (e.g. brine) formed during on-ship processing that will require special handling and disposal. The level of water-borne effluents depends on the degree of processing that is conducted aboard the vessels during harvesting.

Two methods are available for unloading the kelp depending on the size of the systems involved. In the case of the small scale concept, utilizing kelp from natural beds, cranes will probably be used to transfer the algae from the ship to the onshore site. For the ocean farm system, the kelp will be shredded and pre-processed on the ships prior to reaching the processing plant. In the latter case, a slurry of chopped algae mixture will be piped from the ship to the shore-based facility. Since some pumping will be necessary to move the slurried mixture, a potential exists for the release of certain air pollutants from the diesel-powered engines. The consumption of diesel fuel is low so that this environmental impact should be minimal.

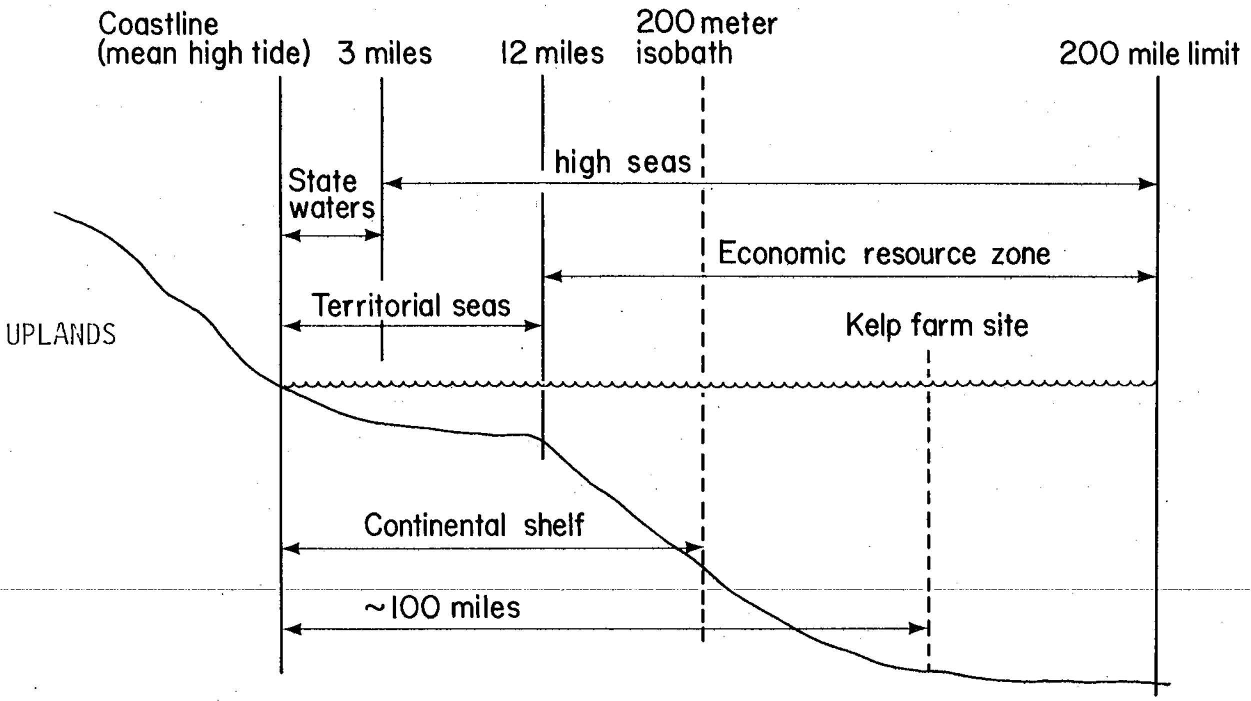

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Fig. 11. Relationship to Kelp Farm Site to Basic Zones of Ocean Jurisdiction

As the pre-processed algal mixture moves through the processing plant environmental residues will be produced at the locations, and in the quantities indicated on Figure 8. Waste water is generated from the shredder, presser and digester components which will eventually be discharged to the sewer system. The waste processing system (see Figure 9) employs a fluidized-bed boiler which provides electricity and heat for the processing system. The fuel for the boiler is sludge which is derived from the pressing of shredded algae. The potential residuals from the fluidized-bed boiler are the ash sludge and the ash and stack emissions that occur after the hot gases from the boiler are passed through a baghouse.

As a final step in the marine biomass system, the processed algae is fed into the anaerobic digester with a residence time of about 10 days and a temperature of 35°C. The gas mixture from the digester is passed through a scrubber to separate carbon dioxide, which is about 60 percent of the gas, from methane. The major environmental residual resulting from this conversion stage of the process is sludge from the scrubber which must be collected for subsequent disposal. The composition of the sludge from the scrubber as well as from the other phases of processing cannot be quantitatively characterized at this time. However, since marine algae will concentrate various heavy metals, the possibility exists for the sludge to contain considerable levels of heavy metals. If any of this sludge is to be used for fertilizer feedstock it will require some level of sterilization.

The specific system design used in this characterization was chosen to minimize the need for external energy input and to minimize environmental pollutant flows. Major flows include only solid char from the fluidized bed boiler (5.2 tons/day for the natural kelp bed system), bag house ash, stack emissions leaving the bag house, and the overflow discharge from the second stage settling tank into a local sewer system (0.058 MGD for the natural kelp bed system). The final distribution of heavy metals and other toxicants between these flows, and the BOD and organic loading of the aqueous discharge cannot be anticipated without measurements from some test, demonstration, or prototype facility.

VIII. CONCLUSIONS

Conclusions within three general areas were reached based on the depth and breadth of this study. These areas are: technical and economic feasibility, environmental impacts, and needed research. Specific conclusions in each are are listed below.

TECHNICAL AND ECONOMIC FEASIBILITY

- Success of the oceanic farm system is directly dependent upon the success of the several major mechanical subsystems. These include: the mooring and anchoring system, the cold water pumping system, and the long term structural integrity of the substrate. Operational success has not been economically demonstrated for any of these components using the systems (e.g. wave power pumps, dynamic positioning, single point mooring) selected for major feasibility studies. The system selected for this study should provide the required operational performance but increase the cost above reasonable levels.
- Aside from being questionably economical, the potential of conventional anchoring system to secure a structure covering hundreds or thousands of acres in several thousand feet of water has not been demonstrated. It is entirely possible that a large ocean farm could not be anchored without having the cost of the anchoring system represent by far the largest cost component of the system.
- Substantial international legal and liability questions still exist concerning the ocean farm. These questions include, but certainly are not limited to U.S. liability for collisions between ships and the substrate or associated fixed platforms, U.S. liability for blockage of fishing rights and lanes, interference with shipping and navigation, U.S. liability for residuals released from the structure or crew quarters, and liability for the cold water plume and its impacts on coastal areas or fishing grounds. The chances for an early resolution of these questions within the Law of the Sea Conference framework should be assessed before additional resources are directed into remaining technical and economic problem areas.

- Neither the ocean farm nor the natural bed system is economically attractive so long as methane is the sole product of the system. Energy costs for the system described in this report are from \$10 to \$30 per million BTU of generated gas. It is probable that this cost could be reduced (possibly to the \$5 to \$8 million BTU range) for a site optimized natural bed system.

- The production of side products (algin and/or feedstocks) appears to be feasible and is economically essential in order to produce a commercially viable system.

- The major components of the oceanic farm system are the pumping and anchoring subsystem. Significant cost reductions in these areas would have a major impact on total system cost.

- The costs calculated in this report differ substantially from those calculated in previous studies (Dynatech, 1978 and Integrated Sciences 1978). These differences are a direct result of several basic assumptions of each study. These assumptions fall into the following categories.

  1) Component cost: This report used unit retail costs for all components. No discounts, wholesaling, or economics of scale for labor requirements were assumed. This was not true for the other two studies both of which had some degree of wholesale and other cost economies.

  2) Dollars listed in this report are 1977 dollars. Significant reduction in total dollar cost are realized by listing costs in other (past) years. For example \$100,000,000 1977 are equivalent to \$70,000,000 1972 dollars.

  3) Structural Component Operation: Both the Dynatech and the Integrated Sciences study assumed that structurally simple mooring and anchoring systems would operate successfully. Reviews of available data for this report indicate that this is not a valid assumption. Similarly, Dynatech and other studies assumed that wave powered pumps are adequate to be the sole power for the deep ocean water pumping system. We saw no basis for using this assumption and assumed a need to provide diesel powered pumps. In reality, diesel assisted wave pumps may be feasible. Thus the operations costs listed here would overestimate total pumping costs and the Dynatech costs would underestimate those costs.

ENVIRONMENTAL IMPACT

- Although the impacts of a large open ocean farm operation have not been studied, there is a potential for significant climatic modifications.
- The ocean system may release numerous chemicals into the sea from the farm structure itself. The chemicals include toxic metals from the anti-fouling paints and organic compounds (e.g. phenol) leached from the supporting liner.
- The upwelling system of the ocean farm concept poses several possible environmental impacts including: possible changes in resident biological communities, entrainment of marine organisms and changes in various physical parameters (e.g. water temperature, salinity, dissolved oxygen, turbidity and nutrient levels).
- The use of recycled sewage sludge effluents as nutrient sources may result in the accumulation of various heavy metals by the marine algae. Toxicity resulting from heavy metal uptake could offset the levels of productivity of the kelp bed. Furthermore, the metals might be present in residues used as feed supplements.
- The harvesting subsystem associated with open ocean farms will include the generation of air emissions (e.g. particulates, NO_x and hydrocarbons) from the diesel-powered harvesting vessels.
- The waste water generated from the shredder, presser and digester will eventually be discharged to the sewer system. The composition of this effluent and the degree of pollution control that is necessary are unknown at this time.
- The major residual resulting from the conversion stage of the process is waste sludge. This material must be collected for subsequent disposal. The sludge may contain considerable levels of heavy metals.
- The institutional problems associated with large ocean farm systems are the jurisdictional issues related to the obstruction of shipping lanes and utilization of coastal fishing locations. A regulatory framework will need to be established.

REQUIRED FUTURE RESEARCH

Research in two areas is indicated by the analysis of this study. First, research into the growth of kelp and especially into various methods of enhancing natural kelp bed growth rates is needed. This research should include the uptake rates and mechanisms of trace elements by kelp (e.g. heavy metals) as well as addressing the effects of increased nutrient concentrations on plant growth rates. Second, research is required in the area of the co-generation of methane and algin using anaerobic digestion techniques. There are indications that this byproduct generation is possible and that it is possible without significantly reducing methane production rates. However, the various proposed processes must be tested and verified.

REFERENCES

Ashare, E., *et al.*, 1978, Cost Analysis of Aquatic Biomass Systems-Final Report, by Dynatech R/D Company for U.S. Dept. of Energy, Fuels from Biomass Branch.

Babbitt, R. 1958 Sewerage and Sewage Treatment 8th ed., John Wiley & Sons, Inc.

Bryce, A. J. 1978 "A Review of the Energy from Marine Biomass Program", Proceedings of Symposium on Energy from Biomass and Wastes, Washington, D. C., August.

Budhraja, V.S. *et al.* 1976. "Ocean Food and Energy Farm Project" Subtask No. 6: Systems Analysis, Vol. 1, Integrated Sciences Corporation, Santa Monica, Ca.

Chynoweth, D.P.; D.L. Klass, and S. Ghosh, 1978 "Biomethanation of Giant Brown Kelp, *Macrocystis pyrifera*", Proceeding of Symposium on Energy from Biomass and Wastes, Washington, D.C., August, 1978.

Clendenning, K.A., 1971 - "Organic Productivity in Kelp Areas", In: *Biology or Giant Kelp Beds in California*, W.J. North, editor, Chapter 12, pp. 259-263.

Flowers, A.B. and A.J. Bryce 1977, "Energy Conversion from Marine Biomass", presented at IXth International Seaweed Symposium, Santa Barbara, CA., August 1977.

Ghosh, S., *et al.*, 1978, "Anaerobic Processes", *Journal of the Water Pollution Control Federation*, Vol. 50, No. 10, pp. 2388-2410.

Goldberg, E.D. 1965 "Minor Elements in Sea-Water", In: *Chemical Oceanography*, J. P. Riley and G. Skirrow, Vol. 1: 163-196, Academic Press, New York.

Hart, M.R., D. deFremern, C. K. Lyon and G.O. Kohler, 1978. "Dewatering Kelp for Fuel, Feed, and Food Uses: Process Description and Material Balances; *Transactions of American Society of Agricultural Engineers* *21*)(1): 186-196.

Hoffman, R.T., A.T. Strickland, and P.J. Harvey, 1976, "Preliminary Design Studies of Substrate and Upwelling Systems. Vol. 2 - Artificial Upwelling in Support of the OFEF Project." Subtask 4 of (Wilcox, H.A., ed) *Ocean Food and Energy Farm Project* by Hawaii Laboratory, Naval Underseas Center.

Hoffman, G.A. and V. Budhraja, 1976, "Systems Analysis, Vol. 4, Processing Subsystem", Subtask 6 of (Wilcox, H.A. ed) *Ocean Food and Energy Farm Project*, Integrated Sciences, Corp., Santa Monica, Ca.

Henriquez, Mark, 1977, "Sewage and Electronics", *California Engineer*, Vol. LVI, No.1, October 1977.

James, A.L. and D. W. Murphy, 1976, "Preliminary Design Studies of Substrate and Upwelling Systems, Vol 1 - Kelp Support Substrate Structures for Use in the OFEF Project", Subtask 4 of (Wilcox, H.A., ed) *Ocean Food and Energy Farm Project*, by Hawaii Laboratory Naval Undersea Center.

Kelco Corp., 1977, Kelco Algin/Hydrophilic Derivatives of Alginic Acid for Scientific Water Control, 2nd ed.

Klass, D. L. and S. Ghosh, 1977. "The Anaerobic Digestion of Macrocystic pyrifera under Mesophilic Conditions", Symposium Papers, Clean Fuels From Biomass and Wastes, January 1977, Orlando, Florida.

Knight, H. Gary, The Law of the Sea: Cases, Documents and Readings, 1976-77 ed. Nautilus Press, Washington, D.C.

Leese, T., 1976. "The Conversion of Ocean Farm Kelp to Methane and other Products", Symposium Papers, Clean Fuels From Biomass, Sewage, Urban Refuse Agricultural Wastes, Orlando, Florida, January 1976.

Nickels, F. J., 1976, "Systems Analysis, vol. 3 - The Harvesting Subsystem. Final Report". Subtask 6 of (Wilcox, H.A., ed) Ocean Food and Energy Farm Project. Integrated Sciences Corp., Santa Monica, Ca.

North, W. J., 1971, "Growth of Individual Fronds of the Mature Giant Kelp, Macrocystis," In: Biology of Giant Kelp Beds in California, W. J. North, Editor, Chapter 3, pp. 123-168, 1971.

North, W. J. 1977, "Marine Farm Studies Progress Report", California Institute of Technology, Corona del Mar, Ca., September 1977.

North, Wheeler J., 1975. Evaluating Oceanic Farming of Seaweeds as Sources of Organics and Energy. NSF/RANN/SE/GI-43881/PR/75/4 California Institute of Technology, 1975.

North, Wheeler J., 1978. The Role of Trace Metals, in: Nutrition of Giant Kelp Macrocystis. W.M. Keck Engineering Laboratories, California Institute of Technology.

Oswald, William J., 1976. Engineering Aspects of Microalgae. University of California, Berkeley Sanitary Engineering Research Lab.

Palmer, M. L. (ed), 1977. Algae in Water Supplies. Public Health Service, Division of Water Supply & Pollution Control.

Pfeffer, J.T., (ed), 1977. Proceedings, Fuels from Biomass Symposium. University of Illinois, Urbana Champaign COO-4225-1.

Pfeffer, J.T. and J.C. Liebman, 1976, "Energy from Refuse by Bioconversion Fermentation and Residue Disposal Processes." Resource Recovery and Conservation. 1 (1976), 295-313.

Schneider, Ronald, Integrated Sciences Corporation, Santa Monica, Ca., 1978. Personal communication.

Sieburth, J., 1969. "Studies on Algal Substances in the Sea, III The Production of Extracellular Organic Matter by Littoral Marine Algae", Journal Exp. Mar. Biol. Ecol. 3: 290-309, 1969.

Tompkins, A. N., 1978, "Energy from Marine Biomass Project - Program Review", General Electric Co., Re-Entry and Environmental Systems Division, Philadelphia, PA.

Troiano, R.A., D.L. Wise, D.C. Augenstein, and R. G. Kespert; 1976, "Fuel Gas Production by Anaerobic Digestion of Kelp", Resource Recovery and Conservation, 2 (1976) 171-176.

U.S. Department of Energy, 1978, Environmental Readiness Document - Ocean Thermal Energy Conversion (OTEC). by Division of Technology Assessment, Office of Technology Impacts, Assistant Secretary for Environment.

Uziel, M., Oswald W., Golueke, L., 1975. Solar Energy Fixation and Conversion with Algal Bacterial Systems/Sanitary Engineering Research Laboratory, U.C.B. NSF/RANN/SE/GI-39216/FR/75/5.

Wilcox, Howard A.,1975. "The Ocean Food and Energy Farm Project", Proceedings of American Association for Advancement of Science, Jan.,1975.

Wilson, Elizabeth, editor, 1977. Sources and Systems for Aquatic Plant Biomass as an Energy Resource. Dynatech R/D Company, COO/4000-77/1

Wright, J., B. Hafen and B. Choi, 1974. "Mooring and Anchoring System Design", in (K. Haven, ed.) Sea Solar Plant - A Feasibility Study. Oregon State University, School of Engineering, Ocean Engineering Program.

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