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The Photosynthesis Energy Factory: Analysis, Synthesis, and Demonstration

Final Report

MASTER

November 1978

Prepared for:
U.S. Department of Energy
Assistant Secretary for Energy Technology
Division of Distributed Solar Technology
Under Contract No. EX-76-C-01-2548

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Prepared by:
InterTechnology/Solar Corporation
100 Main Street
Warrenton, Va. 22186
Under Contract No. EX-76-C-01-2548

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Division of Distributed Solar Technology
Washington, D.C. 20545

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THE PHOTOSYNTHESIS ENERGY FACTORY:
ANALYSIS, SYNTHESIS, AND DEMONSTRATION

ABSTRACT

This quantitative assessment of the potential of a combined dry-land Energy PlantationTM, wood-fired power plant, and algae wastewater treatment system demonstrates the cost-effectiveness of recycling certain by-products and effluents from one subsystem to another. Designed to produce algae up to the limit of the amount of carbon in municipal wastewater, the algae pond provides a positive cash credit, resulting mainly from the wastewater treatment credit, which may be used to reduce the cost of the Photosynthesis Energy Factory (PEF)-generated electricity. The algae pond also produces fertilizer, which reduces the cost of the biomass produced on the Energy PlantationTM, and some gas. The cost of electricity was as low as 35 mills per kilowatt-hour for a typical municipally-owned PEF consisting of a 65-MWe power plant, a 144-acre algae pond, and a 33000-acre Energy PlantationTM. These costs are virtually identical to the cost of coal-derived electricity at a coal cost of \$1.50 per million Btu. Coal- and PEF-electricity costs would be 23 mills per kilowatt-hour for plants larger than 500 MWe.

Using only conventional or near-term technology, the most cost-effective algae pond for a PEF is the carbon-limited secondary treatment system. This system does not recycle CO₂ from the flue gas. Cost-effective expansion of the algae pond to allow treatment up to the phosphorus-limit production of SNG with pond recarbonation is contingent on the development of the operational ability to maintain nitrogen-fixing algal populations, and on a 25-percent cost-reducing innovation in process design.

Analysis of the Energy PlantationTM subsystem at 15 sites revealed that plantations of 24,000 to 36,000 acres produce biomass at the lowest cost per ton. At the most favorable sites, biomass can be produced and delivered for \$17 to \$20 per oven-dry ton (municipal financing), equivalent to \$1.00 to \$1.16 per million Btu. Energy consumed internal to the PEF amounts to 3 to 5 percent of the plantation energy output. Major factors in the cost of biomass are land rental, fertilizer, and equipment depreciation, each accounting for about a quarter of the total cost.

The following sites are recommended for more detailed evaluation as potential demonstration sites: Pensacola, Florida; Jamestown, New York; Knoxville, Tennessee; Martinsville, Virginia; and Greenwood, South Carolina.

A major possible extension of the PEF concept is to include the possibility for irrigation. An irrigation system could be useful in allowing wastewater to be applied directly (after primary sedimentation) to the Energy PlantationTM, thereby achieving and even improving the synergy (water use and CO₂ recycle as well as nutrient recovery) between the PEF subsystems at possibly lower cost.

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Many individuals made significant contributions to the work performed on this project.

First of all, the concept of the Photosynthesis Energy Factory (PEF) was devised jointly by Dr. G. C. Szego of InterTechnology/Solar Corporation and Dr. W. J. Oswald of the University of California at Berkeley.

The efforts of several people with specialized knowledge of the various subsystems of PEF were required to make this project successful. These individuals deserve personal recognition, and they include the following at InterTechnology/Solar Corporation: Dr. L. A. Alexander, C. H. Harmer, Dr. J. F. Henry, D. E. Ludwig, Dr. W. B. Scholten, and C. W. Vail.

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Malcolm D. Fraser
Project Manager

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I. INTRODUCTION AND SUMMARY

A. Concept of the Photosynthesis Energy Factory

The crisis developing the last few years from the scarcity and costliness of fossil and nuclear fuels has motivated innovative research into alternative sources of energy, including using plant matter as fuel and recovering energy from residues of various types. The idea of using agricultural and forest crops as fuel is neither new nor innovative. Plant matter is an easily usable fuel, a renewable resource, and an environmentally clean fuel. However, little attention has been given, until recently, to the possibility and advantages of growing land plants purposely and optimally for their renewable fuel value.

The Energy PlantationTM concept developed at InterTechnology/Solar Corporation (1,2,3) under the direction of Dr. G.C. Szego is an innovative, systematic approach to producing a practical and economic fuel from plant matter on a large scale. Ultimately, the fuel derives from solar energy, which is collected and stored in the growing plants. The plantation is designed and operated to minimize the cost of the plant material produced by carefully choosing the appropriate plant species, planting density, and harvest schedule for each plantation site. A discussion of the design, operation, and economics of the Energy PlantationTM has already appeared in the literature (4). In-depth engineering studies by InterTechnology/Solar (5,6) have established that, depending upon the location of the plantation, the cost of such perpetually renewable clean fuel in its solid as-fired form is less than \$1.30 per million Btu of gross heating value (\$1.23 per kJ).

The harvest of plant matter can be used directly as a clean solid fuel, or it can be processed into some other fuel form. Currently, there is much interest in the idea of converting plant matter into synthetic natural gas (SNG), either by pyrolysis or by anaerobic fermentation. However, to date, research and laboratory experimentation have concentrated

on studying the conversion of municipal solid waste, animal wastes, agricultural residues, and aquatic plants, such as algae, seaweed, and water hyacinth.

No substantive work has been done to study a process for producing SNG from the woody biomass that would be produced from an Energy PlantationTM. Indeed, a recent paper (7) has pointed out the problems, as well as the potential, for the development of such a process.

Another alternate source of energy, which also offers the additional advantage of decreasing the environmental impact associated with the disposal of wastewater and residues, is the concept of growing algae in shallow ponds. Algae ponds are open shallow ponds in which algae and bacterial populations symbiotically utilize sunlight and nutrients to produce cell mass. The earliest application of the algae pond concept is the stabilization pond. Stabilization ponds have been used by small communities for years as a means of treating domestic wastewater. In construction and operation, these ponds are the essence of simplicity. The main requirements are land and a favorable, sunny climate. Currently, there is a trend toward the use of algae ponds as finishing ponds in integrated municipal and waste treatment. The ponds operate in series to "remove" both BOD and phosphorus by tying up these components in cell mass. In an algae pond system for recovering energy from various residues, the algae would be digested anaerobically to yield a methane-containing gas, which would be processed into SNG.

As long as 20 years ago, work was undertaken by Dr. W. J. Oswald and others at the University of California at Berkeley to develop a system utilizing the algae pond concept both to treat waste and to produce energy. The technical problems were essentially tied to integrating the components and optimizing their operation. The components themselves--the algae pond, the digester, and the sedimentation, separation, and finishing stages--were already being used in waste treatment. The work

over the last 20 years has concentrated in three areas: (1) identifying and quantifying algal growth-limiting factors (nutrients, species characteristics, and climatological parameters); (2) maximizing gas production from anaerobic fermentation, and (3) optimizing the system with respect to gas production, residue uptake, land utilization, and cost-effectiveness.

Both the Energy PlantationTM and the algae pond can contribute to the solution of the population, resources and energy problems facing us. The Energy PlantationTM produces environmentally clean and renewable solid fuels. The algae pond treats our wastes, thus keeping our environment cleaner, and provides a way to recover materials and energy from various residues. Recently, it became apparent that they could better accomplish these missions when the two are integrated to form one composite system. Figure I-1 illustrates the concept as it was first recognized.

In short, each produces a by-product that can be used to advantage by the other. The carbon content of sewage limits the production of the algae pond, but carbon dioxide, a by-product of combustion of solid Energy PlantationTM fuel (which currently appears to be the best way of using plant matter as fuel), can be supplied to increase productivity of the algae pond. Likewise, the waste heat from the boiler and the electrical generator can benefit a number of algae pond processes, including the algae pond itself and the algae digester. Even the ash resulting from burning the solid fuel can be used to condition the sludge generated in the algae digester. The sludge generated as a by-product of the algae pond provides a source of inorganic nutrients and water for the Energy PlantationTM. In this way the plantation provides an ideal disposal site for the sludge.

The Photosynthesis Energy Factory (PEF) is a synergistic combination of the dry-land Energy PlantationTM and the algae pond which can produce on a perpetually renewable basis nonpolluting and totally domestic fuels from

marginally useful land, solar energy, and various residues. Simultaneously, from different parts of the PEF, chipped solid fuel is produced, from which electricity is generated, and methane or SNG is recovered from waste CO₂ and municipal or industrial wastewater. Incidental economic benefits--which are significant--include secondary or tertiary treatment of municipal and industrial effluents, and the complete elimination of the need for a sanitary landfill for disposal of the resultant sludge. The PEF is not merely a combination of convenience, but a truly interactive utilization of materials and energy. What was once a waste by-product with only a discard value is now a critical raw material for the enhancement of the operation of the other aspect of this combined process.

FIGURE I-1

THE PHOTOSYNTHESIS ENERGY FACTORY

B. Description of Project

The objective of this project was to study the concept of the Photosynthesis Energy Factory and its characteristics and apparent benefits, and to develop preliminary plans for a demonstration system. The project was divided into three parts or tasks. The objective of one task was to analyze the concept of the PEF, with particular emphasis on the complementary and synergistic aspects of the system. A second task was concerned with the analysis and selection of potential sites. The final task was to develop preliminary designs and associated cost estimates for a proposed demonstration system at a few of the best sites.

To analyze the interactive effects of combining a dry-land Energy PlantationTM with an algae pond system, a comprehensive techno-economic model of a PEF was developed. This model was put together on the basis of available information and data on state-of-the-art technology essentially available today. The University of California at Berkeley, as a subcontractor, was responsible for supplying state-of-the-art data on algae pond performance and costs. Information on the practical design and operation, and costs of wood-fired power plants was supplied by Mr. S. Hunter W. Brooks, a consultant.

In the model, each subsystem of the PEF is described by a set of equations which relate the system outputs to the system inputs as a function of the design variables. The model also includes the estimated costs involved in building and operating the system. Sensitivity analyses were done with the subsystem models to identify the most influential parameters on which research might be done to improve the concept.

For the twin purposes of defining the applicability of the PEF concept and selecting the best site for a demonstration PEF project, data were gathered on the characteristics of land, the availability of municipal

and industrial effluents and residues, and the supply and demand for energy at a wide variety and number of potential sites. First, an inventory of required resources was defined for a potential site. A format was developed for handling this data base, and a number of suitability indexes were defined for evaluating the site data. Data were obtained from a number of sources in the literature as well as from state energy offices on a large number of potential sites. As the result of this site selection procedure, a number of sites were chosen for analysis by means of the techno-economic model.

The model was then used to design a demonstration PEF system at each of the selected potential sites. This preliminary design illustrates for a specific site the benefits and the impact to be expected from a demonstration PEF project. Estimated costs are provided also for each demonstration PEF. Comparing these preliminary designs and their costs was then done to show where and under what conditions a PEF would be expected to be cost-effective in recycling wastes and producing fuels from biomass which would be competitive with presently used fuels.

C. Summary

1. Site-Selection Procedure

The goal of the project task concerned with site selection was to identify potential sites for a demonstration PEF for consideration in the demonstration design task. Thus, in the site-selection task, a multitude of sites was considered to pick a few sites where the necessary resources could be found to mount a successful PEF demonstration. These sites selected as a result of the work of the site-selection task were then further evaluated with the PEF techno-economic model to determine the potential benefits of a PEF demonstration. Because local site-specific factors such as the degree of local participation could be the most crucial determinants of the suitability of a site for a demonstration, the final determination of a demonstration site cannot be made until these local factors can be evaluated in greater detail.

The overall goal of the site-selection task was accomplished by means of two subtasks. The first subtask was to develop an appropriate site-selection procedure, and the second was to use the procedure to screen potential sites to select candidates for further evaluation with the PEF model. As the first step to develop a methodology which could evaluate sites according to the resources found at each site necessary for the establishment and use of a PEF, the resources needed for a PEF were identified.

All resources and services needed at a site for a PEF could be conveniently grouped into three artificial categories--the physical environment, raw materials and resources, and market for PEF products and services. In the physical environment category, factors influencing the establishment of a PEF at a site include climate--rainfall pattern, temperature profile, and insolation--and soil qualities. Important raw materials and resources include land availability and capability, forestry materials, wet organic effluents, dry organic resources, cooling water sources, and labor pool. The market for PEF products and services includes the market for electricity, steam, and gas; possible use of cull trees; need for waste treatment; and need for jobs.

Although data on all of these PEF site characteristics are necessary in the evaluation of a PEF system at a particular site, some of these characteristics are more influential than others in discriminating between sites in a site-screening procedure. Particularly influential are the site characteristics relating to land availability and capability. Because one of the major objectives of a demonstration project would be to demonstrate the feasibility and the economics of the Energy PlantationTM subsystem which would be strongly influenced by land characteristics, quantitative indexes were considered to evaluate land characteristics at potential sites.

Land thought to be suitable for Energy Plantations is defined as underused or marginal land having little or no agricultural, recreational or other uses. Typical suitable land includes abandoned farms, noncommercial forests, unmanaged grazing areas and ranges.

Four indexes were chosen to characterize land at potential sites: (1) available acreage of suitable land; (2) suitable land density; (3) suitable land capability; and (4) relative value of suitable land. To evaluate the available acreage, the county where the possible PEF site is located and counties surrounding that county in some cases were surveyed using the U.S. Soil Conservation Service Conservation Needs Inventory (8) to identify marginal or underused acres. Surrounding counties were used in some cases when they fell within a 30-mile radius of the possible PEF site. The total available acreage was thus estimated for a possible site. The suitable land density index is the ratio of the total suitable acreage at a site to the acreage of the geographic area within which the various land parcels making up the total suitable land are distributed. This index has been found to influence the operation schedule of the plantation, and hence the economics.

The productivity of the various land capability classes has been shown to relate to the investment required to farm each class of land. The return on marginal land is about three-quarters of the return on average cropland. Thus, the values for this index compare the weighted average of all the suitable acres at a site with average cropland, which has the value 1.00.

In general, the value of farmland depends to a large extent on its relative productivity, which is quantified by the land capability index derived above. However, the absolute real-estate value of land depends on a number of factors, of which agricultural productivity is only one. The relative use value index for suitable plantation land at a site is a weighted average value calculated by combining the productivity values for the classes of land present at a site with the local cost of land.

In addition to the availability of land for a biomass plantation, other resources and services are needed at a site for the establishment of a demonstration PEF. However, some of these other resources and services are difficult to quantify, or their quantification does not necessarily aid in discriminating between potential PEF sites. It was decided that it would not be productive to try to derive a numerical site-ranking criterion, which would attempt to assign numerical values to these resources and services. Even if weighting factors were used to attempt to balance the weights of the various resources, weighting factors would be quite arbitrary and a matter of judgment, and combining the numerical factors to arrive at one number which would characterize the desirability of a site would be quite artificial.

Therefore, to recognize the importance of some of these unquantifiable resources and services, their presence or absence at each site is simply noted. The desirability of a particular site must, therefore, be considered a matter of judgment on the basis of the whole body of data and information. The resources and services considered as part of this qualitative analysis are:

- (1) Market for electricity.
- (2) Market for SNG.
- (3) Sufficient rainfall for an Energy PlantationTM
- (4) Labor for operating the PEF.
- (5) Alternate source of dry residues for supplementing the fuel to the boiler.
- (6) Wet organic residues as additional input to the algae pond.
- (7) Cooling water for the power plant.
- (8) Possible local participation in a PEF project.

Of these factors, possibly the most important for the purposes of siting an ERDA-sponsored demonstration PEF project--aside from sufficient rainfall--is the possibility of local participation in a PEF project, and it is not possible to quantify this factor at the present time.

The screening procedure outlined above, consisting of quantitative and qualitative indexes, was tested for its discriminatory powers. Data were assembled and analysis performed for some 70 sites in the eastern United States. These 70 sites were picked originally by applying three constraints: (1) there was adequate rainfall, (2) there was information to support our choice of at least one biomass crop, and (3) there was a need for additional local electrical generating capacity.

The first conclusion to be drawn was that there was no one or a few sites that were obviously better relative to the remainder. When the 70 sites were ranked in the four quantitative categories from best to worst, over half of the sites had to be screened in each category to find one site which appeared in all four categories. The site identified in all four categories--Jamestown, New York--was then compared index by index with other sites whose indexes were at least as good as, or better than, any three out of these indexes for Jamestown. Two groups of sites were identified. For one group, the land capability class was lower. The use value was higher for the second group of sites, indicating that the use of those sites would be comparatively more expensive to obtain. The sites discussed here are shown in Table I-1. The second conclusion was that the qualitative indexes were important to the screening procedure, particularly public participation.

After the screening procedure was developed and tested, data were gathered on a large number of sites, and the procedure was used to show that few of those sites offered the right mix of inputs and outputs necessary for the successful demonstration of the PEF. The first step was to gather data from local sources. The second step was to reduce the collected data by the screening procedure to identify potential demonstration sites which would be worthy of further consideration and analysis in the next project phase.

TABLE I-1
SITE SELECTION TEST

<u>Qualitative Screening</u>								
<u>Site</u>	Participation	Cooling Water	Labor	Demand for Electricity	Demand for Gas	Dry Residues	Wet Residues	Rainfall
Kissimmee, FL	0	+	0	+	+	0	0	+
Chanute, KS	0	0	0	+	+	+	+	+
Natchitoches, LA	0	+	0	0	+	+	+	+
Minden, LA	0	+	0	+	+	+	+	+
Yazoo City, MS	+	+	+	+	+	+	+	+
Jamestown, NY	0	+	+	+	0	+	+	+

Quantitative Screening

<u>Site</u>	Suitable <u>Acres(1000's Acres)</u>	Land <u>Density</u>	Land <u>Capability</u>	Use <u>Value</u>
Kissimmee, FL	523.26	0.62	0.77	317
Chanute, KS	220.59	0.21	0.54	166
Natchitoches, LA	413.54	0.51	0.79	444
Minden, LA	308.66	0.37	0.79	448
Yazoo City, MS	178.98	0.30	0.64	224
Jamestown, NY	150.77	0.20	0.74	305

+ = Positive indication of supply of resources or demand for service.

0 = Uncertainty surrounding supply of resource on demand for service.

* The site selection analysis included originally 70 sites (identified by ITC/Solar) in the eastern United States characterized by adequate rainfall, evidence of potential growth of a biomass crop, and a need for additional local electrical generating capacity.

Inquiries were sent to the energy office, land planning office, and power plant siting office of each of the 48 conterminous states (see Appendix E). The questions asked were purposely general in tone to elicit opinion as well as statistical fact. Forty-one states responded. From the responses, at least one site which superficially met our selection criteria could be identified in every state. These sites are shown in the map in Figure I-2. In addition, ten of these sites were identified by a state planning agency or energy office where it was perceived that the PEF could be part of the solutions to local problems. These ten sites were analyzed according to the screening procedure developed earlier. This analysis is shown in Table I-2. One of the ten sites, Yazoo City, was identified both by our testing procedure and by responses from the states.

The fifteen sites from Tables I-1 and I-2 were evaluated by means of the PEF techno-economic model to illustrate the benefits and costs of PEF at particular sites and to aid the process of selecting a few sites to be considered in a more detailed analysis in the next project phase.

FIGURE I-2

POTENTIAL SITES FOR THE PHOTOSYNTHESIS ENERGY FACTORY

TABLE I-2
ANALYSIS OF STATE-IDENTIFIED SITES

<u>Qualitative Screening</u>								
<u>Site</u>	Participation	Cooling Water	Labor	Demand for Electricity	Demand for Gas	Dry Residues	Wet Residues	Rainfall
Pensacola, FL	+	+	+	+	+	+	+	+
Maysville, KY	+	+	0	+	+	0	+	+
Traverse City, MI	+	+	+	+	+	+	+	+
Bemidji, MN	+	+	+	+	0	+	+	+
Yazoo City, MS	+	+	+	+	+	+	+	+
Hammond, NY	+	+	+	0	0	+	+	+
Greenwood, SC	+	+	+	+	+	+	+	+
Knoxville, TN	+	+	+	+	+	+	+	+
Caldwell, TX	+	+	+	+	+	+	+	+
Martinsville, VA	+	+	0	+	0	+	+	+

Quantitative Screening

<u>Site</u>	<u>Suitable Acres</u> <u>(1000's Acres)</u>	<u>Land</u> <u>Density</u>	<u>Land</u> <u>Capability</u>	<u>Use</u> <u>Value</u>
Pensacola, FL	149.06	0.14	0.95	620
Maysville, KY	204.06	0.40	0.48	276
Traverse City, MI	112.01	0.16	0.60	445
Bemidji, MN	178.13	0.11	0.85	167
Yazoo City, MS	178.98	0.30	0.64	224
Hammond, NY	234.56	0.13	0.68	48
Greenwood, SC	139.94	0.13	0.74	324
Knoxville, TN	90.35	0.16	0.52	652
Caldwell, TX	178.13	0.42	0.82	467
Martinsville, VA	140.22	0.14	0.60	357

+ , 0 = See Table II-2

2. PEF Subsystems and Subsystem Models

a. General

The Photosynthesis Energy Factory (PEF) comprises three major subsystems-- the dry-land Energy PlantationTM, a wood-fired power plant, and an algae production system. Various streams of energy and materials flow between these subsystems, as shown in Figure I-3. Wood ash, carbon dioxide, and waste heat flow from the power plant to the algae pond; sludge fertilizer and some reclaimed water flow from the algae pond to the Energy PlantationTM; and wood fuel flows from the Energy PlantationTM to the power plant. To analyze the interactions between the subsystems as the result of these energy and material flows, a comprehensive techno-economic model was developed to describe the performance and the cost of the PEF.

The three subsystem models were developed with the aid of information and data that have already been developed on the subsystems as the result of previous studies. New data and new concepts have been introduced into the models wherever possible. These subsystem models are biological-engineering-economic models developed in sufficient detail to represent the important variables and variable-parameter interactions which influence subsystem performance and costs. Of the three subsystem models, the most comprehensive and the most complex is the Energy Plantation model, which is a complete design model rather than simply an input-output model.

By and large, the models were developed using available technology as much as possible because one major use of the models is to provide preliminary designs of a demonstration PEF at potential sites. This feature does restrict the use of the models to predict the near-term potential of PEF with improved technology. However, the models can be updated and refined easily enough to include technology which will soon be available so that the near-term potential of the PEF can be evaluated in a more definitive manner.

FIGURE I-3

SCHEMATIC FLOW DIAGRAM OF PHOTOSYNTHESIS ENERGY FACTORY

b. Algae Pond Subsystem

A technical and economic model of an algae pond-based waste treatment system has been developed for use in conjunction with the Photosynthesis Energy Factory. The main process elements involved in the algae pond system include: the algae growth ponds, in which carbon, nitrogen and phosphorus are removed from the wastewater and assimilated in algal cell mass; algae harvesting equipment; the digester, which will anaerobically digest primary solids and algal solids; the drying beds, which will dry the algal sludge for use as fertilizer; and the gas cleanup train, which includes carbon dioxide scrubbing, gas drying and pipeline compression.

The algae pond system has several advantages in terms of energy conservation and production. At the most basic level, it is a much less energy-intensive form of waste treatment than conventional activated sludge plants. Because of the use of power plant waste heat for digester heating, there is a much higher net yield of digester gas that can be used for its heating value. The energy balance for the algae pond system can be looked at from two perspectives: (1) the actual conversion efficiency from solar insolation to usable fuel, i.e., SNG, or (2) the net energy production based on a gross energy yield of SNG, less the energy required to operate the algae pond system. After conversion losses for each step of the fixation and conversion processes, and parasitic power requirements are deducted, the overall sunlight-to-fuel conversion efficiency of the algae pond system is on the order of 0.33 percent.

This analysis approach does not fully take into account the advantages of energy conservation, i.e., the use of less energy-intensive methods for waste water treatment and fertilizer production. Table I-3 gives an energy balance for a nitrogen-limited system on this basis. Energy inputs to the system include: mixing power requirements; compressor and sparger system blower

TABLE I-3
ENERGY BALANCE FOR 1-MGD NITROGEN-LIMITED SYSTEM*

Basis: 1 year of operation

ENERGY INPUT**

Lift stations and inter-pond pumping, 100 ft head	0.15 x 10 ⁶ KWH
Mixing:	
2 hr/day @ 30 cm/sec	0.10 x 10 ⁶ KWH
22 hr/day @ 5 cm/sec	0.18 x 10 ⁶ KWH
Compressors and sparger system blowers	0.088 x 10 ⁶ KWH
Digester heating - - provided by power plant condenser	0
Microstrainer (12):	
Head loss, 0.5 ft /stage	
Backwash pumps	0.003 x 10 ⁶ KWH
Facility construction, treatment chemicals	??
	<hr/>
	0.52 x 10 ⁶ KWH

ENERGY YIELD

SNG	5.2 x 10 ⁶ SCF	1.5 x 10 ⁶ KWH
Fertilizer, Ammonia equivalent		0.66 x 10 ⁶ KWH
Wastewater Secondary treatment equivalent(11)		0.22 x 10 ⁶ KWH
		<hr/>
		2.4 x 10 ⁶ KWH
Net Yield = 2.4 x 10 ⁶ - 0.5 x 10 ⁶ = (78% of Gross Yield)		1.9 x 10 ⁶ KWH
		(6.4 x 10 ⁹ Btu)
Net Energy Production Density = 6.4 x 10 ⁹ Btu ÷ 49 acres		1.3 x 10 ⁸ Btu/acre

* Includes energy savings attributable to alternate production of fertilizer and to conventional waste treatment

** Values are for onsite power usage, not primary generation

requirements, and pumping requirements for the microstrainer harvesting system. No energy inputs have been assumed for the actual facility construction or production of treatment chemicals for the plant. When this scheme is used, the net yield of energy is 78 percent of the gross energy yield. For the system described, the net energy production density is 1.3×10^8 Btu/acre-year.

A computer model has been developed to predict the performance of the algae pond system using a variety of process options. Initial calculations with the model determined the most cost-effective set of process options, which was then used for the final analyses for the potential sites.

The performance model reflects and is limited by the current state-of-the-art in algae growth. Mass culture of algae is a rapidly developing area; however, several important, basic relationships have yet to be quantified. As a result, several parameters which eventually will be the output of the technical design must be introduced as input data. For example, the level of wastewater treatment is only partially predictable by the process options selected. Nutrient removal efficiencies must be input for each different level of treatment. Similarly, the solar conversion efficiency cannot be predicted by the model and must be input. Finally, algae digestion is essentially a "black box" operation at this point. This fact prevents a quantitative assessment of nitrogen and phosphorus mass balances in the system. Within these limitations, equations have been developed to predict: (1) the flows and (2) the required equipment sizes for the various process operations.

The raw wastewater coming into the PEF is treated first with primary sedimentation. Experiments with algae production on sewage have consistently

used settled sewage as a substrate. Primary sedimentation equipment for the algae pond system is identical to that in a conventional waste treatment plant. Since it has as its basis the physical phenomenon which takes place in sedimentation, overflow rate is most widely used in design of sedimentation facilities and is used in this model.

The ultimate amount of algae that can be produced from a given wastewater stream is a function of the nutrient makeup of that stream and the available nutrient resources. To determine the maximum annual algae production, it is necessary to develop nutrient balances around the entire algae pond system. Of the three major nutrients in municipal wastewater--carbon, nitrogen and phosphorus--carbon is normally the first to be exhausted and consequently to limit growth. Nitrogen is normally next to limit biomass production. A carbon balance around the algae pond system is made in the model to determine the amount of flue gas carbon dioxide required to attain the higher theoretical production of the nitrogen or phosphorus limit.

The average annual per-acre yield of algae is based on a solar conversion efficiency. In this model the conversion efficiency is an input parameter. The calculation of annual yield is preceded by a screening of monthly average ambient temperatures at a given site to determine the number of months the system can be operated annually. With proper selection of algal species, temperature does not influence growth rate until the average temperature drops to below around 5°C, or 40°F. Below this temperature, the growth rate declines rapidly and the required nutrient removal efficiencies cannot be met. During these months, the wastewater must be stored for subsequent treatment. Heating the pond with waste heat from the power plant is not considered in this model.

The design requirement for calculation of per-acre yield involves meeting necessary wastewater treatment standards in the worst-case month. The

operating month with the lowest average daily insolation is selected as the design case. Because conversion efficiency is inversely proportional to light intensity, this month will have the highest value of conversion efficiency. The design value used for this system is four percent conversion efficiency. The resultant yield, when multiplied by the number of operating months, will give an equivalent annual yield.

The high-rate oxidation ponds envisioned for the algae pond system are made up of very shallow ponds, on the order of 10 inches deep. In this case, the intent is to maximize production of algal cell mass. Photorespiration and the formation of anaerobic zones in the ponds must be avoided. This necessitates a certain minimum level of mixing and pH control. The ponds are operated as continuously back-mixed biological reactors. They are designed to allow a variable retention time, variable depth, and variable algal density. With the nutrient levels available in sewage, the pond growth system is light-limited.

Unlike algal growth in conventional stabilization ponds, the algae in high-rate ponds are harvested for subsequent digestion to SNG. Reliable low-cost harvesting has been a major problem in mass algal culture. A variety of methods has been presented in the literature. Research at the University of California at Berkeley (UCB) indicates that microstraining may be an effective compromise between producing a high-solids-content, relatively pure algal sludge at high cost and producing a sludge unacceptable for digestion at low cost. Microstraining is low in cost and reasonably effective on larger algal species. A microstrainer is a revolving drum coated with a fine mesh screen which strains solids from the influent stream. Sizing of microstrainer equipment is based on the required submerged surface area on the drum per unit flow. Dissolved air flotation was also examined as a candidate method for algae harvesting.

While there are very little pilot-scale data concerning anaerobic digestion of algae, lab-scale work indicates that algal cells behave much like conventional waste treatment solids. Gas yields appear to be similar to conventional systems. As is true in conventional digestion, operating temperature is an important design parameter. Based on data from UCB, operation in a mesophilic range (up to 110°F) appears to be most cost-effective. At 95°F, a retention time of over 11 days is required to prevent washout of methane-forming bacteria. Because of its relation to the biological phenomena which occur in digestion, retention time is the most suitable design parameter and is used in this model. At 95°F, gas production is approximately five cubic feet of methane per pound of algal volatile solid introduced to the digester.

Digestion of primary solids and algae results in a 50-percent reduction in settleable solids. Dewatering of this digested sludge is necessary to minimize transportation costs in delivering the sludge to the Energy PlantationTM. Work with algae dewatering at the University of California at Berkeley indicates that sand drying beds are suitable for this purpose. Underflow from the sand beds is recycled to the algae ponds. Fly ash from the power plant can be used as a dewatering aid on the sand beds and will add nutrients to the sludge going to the Energy PlantationTM. Sand bed cost is primarily a function of required surface area. The required surface area is calculated based on a design solids loading.

The raw gas evolved from the digester is approximately 65 percent methane and 30 percent carbon dioxide. To produce pipeline-quality SNG, it is necessary to remove the CO₂ from the digester gas. The least costly of the chemical absorption systems for CO₂ removal is the Benfield hot potassium carbonate system. The SNG coming from the Benfield unit will then go to a glycol dryer, which is the most widely used method for drying natural

gas. The drying system dries the gas to approximately seven pounds of water vapor per million cubic feet of SNG. When the gas leaves the dryer, it is compressed to 1000 psia for pipeline transmission. Sizing and cost estimation of the scrubbing, drying, and compression units are based on the gas flow to each of the systems.

One of the important innovations of the PEF concept is that carbon dioxide from the power plant will be introduced into the high-rate oxidation ponds to allow greater production of algae from the wastewater stream. Carbon is normally the limiting nutrient in municipal wastewaters. Nitrogen is normally the next nutrient to limit growth. To reach the phosphorus growth potential, it will be necessary both to add carbon dioxide and to maintain nitrogen-fixing species of algae in the pond. Application of carbon dioxide to the pond cells will also have the added benefits of sparging photosynthesis oxygen and reducing the pH. Without this carbon dioxide transfer, the pH would rise as bicarbonate is removed from the pond waters.

The recarbonation system for the algae ponds is modeled after a diffused air system in a conventional activated sludge plant. The system design is based on the required gas flow. Experimental data are available for mass-transfer correlations under the pond conditions. Engineering calculations indicate that the transfer efficiency in the shallow oxidation ponds will be on the order of 15 percent.

A cost model of the algae pond system has been developed to allow evaluation of the life-cycle cost of various processing schemes. Equations for installed capital costs and operating and maintenance (O and M) costs have been developed for each piece of equipment. Where possible, data for the actual piece of equipment to be used were located and used for cost equations.

In formulating the cost equations, the prevailing values for land cost, pipeline gas cost, labor rates, and power costs for the specific candidate site were used. The wastewater treatment credit was taken from a national survey of the capital costs of wastewater treatment plant construction done by EPA. This study found that the amortized capital cost of construction of secondary plants was approximately 52¢ per thousand gallons treated (27). A separate study estimated the operation and maintenance costs for a secondary treatment plant at approximately 36¢ per thousand gallons treated, yielding a total cost of approximately 88¢ per thousand gallons (28). A scale-up factor of 1.52 was used for escalating costs for tertiary treatment (26).

Two methods have been used for evaluating the life-cycle cost of the various algae pond systems. The utility method involves mixed financing for obtaining necessary capital. A portion of the annual income is in this case subject to income tax. An average discount rate of 11.1 percent was used for the utility financing method. Alternatively, a municipal financing method may be used. In this case, the municipality finances the project through low-cost municipal bonds. No tax obligation is incurred. The discount rate is equal to the interest rate on the bonds. In this case 6.375 percent per annum was assumed. This is the discount rate set by the Water Resources Council for estimating water resources projects in fiscal 1977. The municipal financing procedure has been chosen for use in the overall analyses of the algae pond system, primarily because this method reflects current practice in treatment systems dealing with municipal domestic wastes.

The output of both the utility and municipal financing methods is an equivalent annual expense for the given algae pond system. This expense can be combined with the gas credit, which is calculated on a life-cycle basis from the local prevailing cost for gas, and the waste treatment credit, resulting in a net annual cash flow. This cash flow may be used to compare

the life-cycle cost and cost-effectiveness of algae pond system process alternatives or for comparing algae pond systems at specific sites. In the analysis of the PEF as a whole, the cash flow from the algae pond system, which is generally positive, is used to reduce the price of the generated electricity.

The combined technical performance and cost model of the algae pond system was used to evaluate a variety of process options, processing sequences, and operating parameters. The base case system was a hypothetical 1-MGD secondary treatment plant in Greensboro, North Carolina. From the analysis, two apparent major influences on the cost-effectiveness of the algae pond system are: (1) months of operation per year; and (2) the level of waste treatment. The model assumes that the wastewater treatment credit must be decreased proportionally to the decrease in operating time during the year.

Table I-4 shows the effect of wastewater treatment level on the cost-effectiveness of the algae pond system. Cash flow decreases as the level of treatment increases. For the case of nitrogen-limited growth, no additional wastewater treatment credit has been taken above the secondary treatment credit. This is because tertiary treatment deals primarily with phosphorus removal. Consequently, expanding the plant to the nitrogen-growth limit is not cost-effective, which is reflected in the high incremental cost of gas (\$32.83/1,000 SCF).

Tertiary treatment using blue-green algae to fix nitrogen is not possible with near-term technology. However, when species control does become available, phosphorus-limited growth systems may be cost-effective. The incremental cost of gas when compared with the carbon-limited base case system is \$12.78/1000 SCF. This value represents the average cost of gas

TABLE 1-4

TECHNICAL AND ECONOMIC EFFECTS OF WASTEWATER TREATMENT ALTERNATIVES

<u>Parameters for 1-MGD Base System</u>	<u>Limiting Nutrient</u>		
	<u>Carbon</u>	<u>Nitrogen</u>	<u>Phosphorus</u>
Pond Area, Acres	25	48	193
Methane Production SCF/Year	3.18×10^6	5.16×10^6	17.6×10^6
Fertilizer Equivalent			
Tons N/Year	32.8	43.8	176.5
Tons P/Year	4.1	7.2	19.5
Capital Cost	\$790,000	\$1,241,000	\$3,294,000
Treatment Credit	Secondary	Secondary	Tertiary
Net Annual Cash Flow	\$213,000	\$152,000	\$58,000
Incremental Cost of Gas* \$/1000 SCF	-----	\$32.83	\$12.78

*Incremental cost is the ratio of the change in the difference between treatment credit and equivalent annual expense to the change in annual gas production, i.e.

$$\text{Cost} = \frac{\Delta(\text{treatment credit} - \text{annual expense})}{\Delta 1000 \text{ SCF Units}}$$

based on a comparison with the carbon-limited case.

over the 20-year lifetime of the project. Assuming a 10 percent annual escalation of gas price, it is equal to a present cost of approximately \$5 per thousand standard cubic feet. To produce gas with an equivalent present cost of \$2/1000 SCF, the equivalent annual expense of the phosphorus-limited system must be reduced approximately 25 percent, which may be attainable.

The algae pond system developed for the base case was applied to each of 15 candidate PEF sites using local data on net evaporation (pan evaporation-precipitation) rate, monthly average insolation and temperature, wastewater flow, and costs. Local costs include the cost of pipeline gas, the cost of labor for operating the plants, and the cost of utilities. The wastewater treatment credit used was a national average for secondary treatment costs. A computer run was made for each site for the carbon-limited case, the nitrogen-limited case, and the phosphorus-limited case. The major factors which influenced the relative value of the cash flow at the different sites were months of operation, the level of treatment, and the plant size. Higher levels of treatment result in lower net annual cash flows and increasing capital cost. The results of the site-specific performance runs indicate that, for the present, a carbon-limited, secondary treatment system will be most cost-effective. Any of the sites in the southeast, where 12 months' operation is possible, are cost-effective.

c. Modeling of the Energy PlantationTM Subsystem

The purpose in studying the Energy Plantation in this task was, first, to develop a techno-economic model of the Energy Plantation and, second, to apply this model to the sites retained for evaluation as potential candidates for Photosynthesis Energy Factory (PEF) demonstrations.

In analyzing the PEF concept, the inputs to the Energy Plantation model are a description of the site being investigated, supplied by the site-selection procedure, and the amounts of nitrogen and phosphorus recycled to the plantation, supplied by the algae pond model. The major outputs of the plantation model are the yearly amount of biomass produced and its cost (in the form of green chips) delivered at the utilization point. These items constitute the major inputs to the power plant model. Manpower and equipment requirements, species suggested for the plantation, and planting, harvesting, and operating schedules for the plantation are secondary outputs of the plantation model. The plantation model can be used independently of the other components of the Photosynthesis Energy Factory model.

i. Energy Plantation Model

The Energy Plantation model comprises nine subroutines listed and briefly described below:

- Land Resources - This subroutine contains and analyzes the site-specific data supplied by the site-selection procedure. The land available for plantation use is characterized by the average size of the plantation parcels, their geographic distribution (plantation density), the quality of the land and its cost, and climate factors.
- Data Base on Plants - This subroutine is essentially a data bank describing the growth characteristics of the candidate species for Energy Plantation applications. Initial and coppice growth of the species are each described

by three parameters as suggested by the ITC/Solar plant-growth model. The dependence of the growth parameters on the planting density in the plantation is also identified. Other data included in the species data sheets are the forest group and land classes in which the species are known to grow, heating values, recommended clone size, moisture content, etc. Data sheets for several varieties of hybrid poplars, eastern and plains cottonwoods, sycamore under various growing conditions, silver maple, black cottonwood, red alder and eucalyptus are included in the data bank. Comparison of experimental yield data with yields predicted from the plant-growth model show that, within the range of validity of the model (age 2 and over and planting densities of about 1500 trees/acre and over), the calculated predicted yields are generally within 5 to 10 percent of the experimental values (the basis of the plant-growth model and the significance of the growth parameters are discussed in Appendix C).

- Nutrient Balance - This subroutine estimates nutrient requirements of the plantation for nitrogen, phosphorus, potassium and calcium. It takes into account the amounts of nutrients removed through periodic harvest of the biomass crop, the amounts of nutrients supplied by the recycled sludge from the algae ponds and ash from the power plant to determine the amounts of nutrients which must be supplied from external sources to maintain sustained productivity of the plantation at the level determined by the plant-growth model for the various harvesting cycles considered.
- Species Selection and Characterization - Potential candidates to be grown in the plantation are selected from the species data bank. The selection is made on the basis of the forest groups and land classes to which the plantation land belongs. The growth parameters of the species data bank are then adjusted to reflect the quality of the land considered for the plantation.
- Plant-Growth Model - For each of the species retained in the species selection subroutine, this subroutine suggests yield-cycle combinations characterized by oven-dry tons per acre-year, planting density, harvesting

cycle (age at first harvest and duration of coppice growth periods), and number of successive coppice harvests taken before replanting. For each species, the best candidate cycles can be selected (maximum yielding cycle as well as cycles supplying a certain percentage of this maximum).

- Data Base for Field Operations - This data bank characterizes the equipment to be used in the field operations. The description includes capacity of the equipment, investment, operating and maintenance repair costs, operating labor and labor costs, and fuel type and consumption. All the equipment considered, except the harvester-chipper, is agricultural or forestry-type equipment currently in use. Prices are early 1977 prices. Characteristics (performance, cost) for the harvester were assumed for a reinforced, heavy-duty machine comparable to a forage corn harvester but capable of handling tree material several inches in diameter.
- Field Operations - The objective of this subroutine is to define the scheduling, equipment inventory, labor force, installation and start-up operations required for each of the yield-cycle combinations selected and retained for analysis in the plant-growth subroutine. The plantation is designed as a self-contained industrial operation comprising supervision and administrative operations, field operations--harvesting, cultivation, fertilization, road maintenance, clearing and replanting, fungicide application and biomass transportation; nursery operation--clone generation and storage; motor pool operations--maintenance and repair, spare equipment and fuel supplies; plantation preparation and installation and plantation start-up. The subroutine takes into account local factors such as climatic conditions making the fields inaccessible, the roads impassable or restricting the harvesting operations. The subroutine also offers the option of selecting several transportation systems, including pneumatic tube delivery of the chips to the point of utilization. Irrigation is not currently included in this subroutine.

- Data Base for Cost Estimates - This subroutine is a data bank containing the costs of supplies such as fertilizers and fuels needed for the cost estimates. These items are site-specific. Values quoted for farm products in March 1977 for various regions or states in the U.S. are used in this data bank. Financial information needed to estimate the cost of biomass are also included--interest rates on debt and equity, fraction of debt, etc.

-Cost of Biomass - In this subroutine, the cost of biomass (\$/green ton delivered) is estimated on the basis of the utility and municipal methods of financing. The resultant printout shows the various components of the overall cost of biomass--investment, operating costs, depreciation, etc.--for both methods of financing.

The various species-yield-cycle combinations selected as a result of the plant-growth subroutine and analyzed in the field-operations subroutine are considered in succession. For each species, the program selects the yield-cycle combination resulting in the lowest cost for biomass. The final cost data used to characterize the potential of a site for biomass production is an average of the data for each of the species considered for the site. This approach was adopted as Energy Plantations are assumed to include a mix of species.

ii. Sensitivity Analysis

The Natchitoches, La., site was used to evaluate the impact of some of the plantation operations or components on the cost of biomass. The following general conclusions were reached:

- high plantation densities (4 to 12 ft²/tree) and short rotations (2 to 3 years for first growth and 2 to 4 years for coppice growth) are generally favored.

The shorter duration of the first growth period suggested by the model is due to the fact that the model selects yield-cycle combinations which maximize the average sustained yearly yield over a complete plantation cycle (first harvest plus several coppice harvests). Thus, the model suggests planting densities and harvesting cycles which optimize land usage during the coppice growth years which contribute most to sustained production (o.d. tons/acre-year).

- the major contribution to the cost of biomass is the yearly operating cost (70 to 80 percent of the biomass cost--see Table I-5). Of these, land rental, nutrients and labor costs are the major items amounting to about 85 percent of the operating costs for both methods of financing.

The cost of nutrients could be lowered by modifying the schedule and method of application of the nutrients.

- the second major item in the cost of biomass is the annual equivalent of the depreciable investment. In the case considered, this investment is on the order of \$6 million or about \$18 per oven-dry ton delivered per year.

- based on the fuel consumption of the plantation equipment and the energy used to produce the nitrogen fertilizer (but not to fabricate the equipment or produce other nutrients), the energy efficiency of the plantation is about 97 percent; i.e., the plantation operation requires only about 3 percent of the plantation energy output. This problem is further discussed in Section III-C-3.

- for plantations larger than about 20,000 acres, the cost of biomass is generally on the order of \$1.20 to 1.30 per million Btu for municipal financing.

- for large plantations (about 40,000 acres and over), pneumatic tube transportation appears to be the best method of delivery of the wood chips. This point should be further investigated for other plantation conditions (land distribution, for instance).

- except for small parcels (about 50 acres), the size of the parcels making up the plantation has little effect on biomass cost for reasonably dense plantations, i.e., high plantation-to-geographic-area ratio. This point should be further investigated.

- changes in sustained yields (o.d. T/acre-year) without modifications to the harvest cycle have a relatively small effect on cost.

TABLE I-5
SUMMARY OF THE FINANCIAL DATA FOR THE NATCHITOCHES, LOUISIANA, SITE
 (36,000-acres plantation, hybrid poplar NE 388-4-2-2⁽¹⁾, 8.52 o.d T/acre-year)

<u>Annual Equivalent</u>	<u>Utility</u>		<u>Municipal</u>	
	\$	%	\$	%
Depreciable Investment	1,634,489	22	938,727	17
Non-depreciable Investment	101,910	1	49,311	1
Federal Income Tax	334,031	4	0	0
<u>Annual Operating Costs</u>				
Fuels	140,080	(1.8)	140,080	(2.5)
Land Rental	1,938,060	(25.6)	1,113,075	(19.8)
Total Labor	972,250	(12.8)	972,250	(17.3)
Administrative and Overhead	194,450	(2.6)	194,450	(3.4)
Supplies - Nitrogen	1,364,972	(18.0)	1,364,972	(24.2)
Phosphorus	42,930	(0.6)	42,930	(0.8)
Potassium	361,063	(4.8)	361,063	(6.4)
Lime	8,863	(0.1)	8,863	(0.2)
Total Nutrients	1,777,828	(23.5)	1,777,828	(31.6)
Others	81,210	(1.1)	81,210	(1.4)
Maintenance and Repair	322,618	(4.3)	322,618	(5.7)
Local Taxes and Insurance	82,160	(1.1)	39,558	(0.7)
Total	5,508,656	73	4,641,069	82
 Total Revenue Required	 7,574,085	 100	 5,629,108	 100
 Product Cost (\$/o.d.T)	 23.84	 -	 17.71	 -
(\$/10 ⁶ Btu)	1.39	-	1.03	-

(1): Planting density: 4 ft²/tree
 Age at first harvest: 2 years
 Coppice growth period: 2 years

- changes on the yield-cycle combinations and the number of coppice harvests have a strong effect on the cost of biomass.

- the uncertainty of the predicted cost of biomass is probably on the order of 10 to 15 percent, which is within the range of variations expected from yearly fluctuations in the climatic conditions.

iii. Comparison of the Selected Sites for Plantation Demonstration

The 15 selected sites were analyzed on the basis of the plantation model discussed in the previous sections. Species retained included hybrid poplars, eastern and plains cottonwoods, silver maple, sycamore (southern and mid-latitude sites) and eucalyptus (Florida sites only). Proposed planting densities are generally between 4 and 12 ft²/tree with harvests (first and coppice) at 2 to 4 years interval.

Table I-6 summarizes the plantation data for the sites. Areas of the plantation are in the range of 27,000 to 36,000 acres. The differences in yearly production are mostly related to differences in land productivities or average sustained yields (oven-dry tons per acre-year); these extend from about 4 o.d.T/a-y (Maysville, KY) to about 9 oven-dry tons per acre-year (Bemidji, MN). The differences in cost of biomass are related to a number of factors, including the investment, land rental, transportation costs and amount of nutrients recycled to the plantation. The differences in investment are influenced by the conflicting effects of reduced productivity per acre-year, which tends to decrease some but not all of the investment cost, and reduced periods of plantation operation due to climate, which tends to increase the necessary investment in harvesting and transportation equipment. The differences in energy efficiency between the various sites result mostly from the variations in the amounts of nutrients recycled from the algae pond to the plantation at the various sites.

The 15 sites were ranked for their attractiveness for demonstration of the Energy PlantationTM concept on the basis of the cost of biomass produced,

TABLE I-6
COMPARISON OF THE MOST PROMISING SITES FOR
ENERGY PLANTATIONTM DEMONSTRATIONS

Sites	Annual Production o.d. T/year	Cost \$/o.d.T	Investment \$/o.d. T-y	Efficiency %
Maysville, KY	152,890	25.95	152.3	2.34
Chanute, KS	277,030	20.27	113.3	2.25
Martinsville, VA	218,333	19.85	28.3	2.31
Caldwell, TX	274,615	22.08	98.7	2.26
Bemidji, MN	249,712	17.27	29.9	2.45
Traverse City, MI	232,313	23.78	37.9	2.43
Hammond, NY	236,781	19.41	31.9	2.42
Yazoo City, MS	208,655	20.06	31.3	2.33
Kissimmee, FL	261,952	18.83	95.9	2.32
Pensacola, FL	197,974	21.27	26.6	2.15
Jamestown, NY	224,641	20.57	31.6	2.38
Greenwood, SC	201,057	17.53	30.0	2.31
Knoxville, TN	150,079	25.79	38.4	1.62
Natchitoches, LA	278,437	19.67	26.3	2.29
Minden, LA	261,401	18.93	26.3	2.32

the required investment and the energy efficiency of the plantation. The three preferred sites are the two sites in Louisiana and Greenwood, South Carolina. As shown in Table I-6, these three preferred sites would require investments of about \$6 million to \$7 million, and would supply fuel at about \$17.50 to about \$19.70 per o.d.T delivered or about \$1.00 to about \$1.15 per million Btu.

d. Power Plant Subsystem

Interactions between the power plant and other components of the PEF are indicated by flow lines in Figure I-3. The fuel is supplied from the Energy PlantationTM. The exhaust gas, heat condenser cooling water, and ash are at least partially supplied to the algae pond system. Dirt from the screener can be redistributed onto the Energy PlantationTM land so that its nutrient value is not lost. The electricity, of course, is the primary output of the power plant and is fed into a power grid for use as demanded by the specific site. Combustion air and tempering air for the chip dryer are supplied directly from the surrounding atmosphere.

The power cycle modeled is a conventional steam Rankine cycle as is used in coal-fired and nuclear power plants. More exotic power cycles such as a gas turbine were not modeled in keeping with the decision that the model should represent "state-of-the-art" equipment which would be readily available for a demonstration system. The system components are similar to those that would appear in a simple coal-fired power plant with the addition of equipment to dry and screen the fuel before it enters the boiler. Storage space for dried fuel is provided in the event that a continuous supply of fuel from the Energy PlantationTM is interrupted.

The steam cycle in the power plant model is a simple cycle consisting of the four basic elements of boiler, turbine, condenser and pump. To calculate the energy transfer rates to and from the steam in each of these components, certain relationships between various steam properties must be known. These include, for example, the relationship between saturation temperature and pressure, the enthalpy of saturated liquid as a function of temperature, the entropy of saturated liquid as a function of temperature, the enthalpy of superheated steam as a function of temperature and pressure and the entropy of superheated steam as a function of enthalpy and pressure. An algebraic expression for each of these relationships was found using least-squares curve-fitting techniques with Steam Table data.

In practice, additional components such as reheaters and feedwater extraction regenerative heaters are included in the steam cycle to increase its efficiency. The model can approximately predict the performance of an extraction steam cycle by including the following two factors in the model: (1) ratio of Rankine cycle efficiency of the extraction cycle to the Rankine cycle efficiency of the simple cycle operating under the same conditions, and (2) the ratio of flow rate of steam through the boiler to flow rate of condensate through the condenser for the extraction cycle. Representative values of these factors were found as a function of turbine inlet steam pressure by analyzing the performance data from ten coal-fired TVA power plants. From these data, it was found that the simple-cycle model could be used to predict quite accurately the performance of extraction cycles using these factors as calculated from correlations with boiler pressure. With these correlations, accurate comparison of the performance and costs between large utility-sized coal-burning and wood-burning power plants could be made.

A correlation for parasitic power for a wood-fired power plant was developed from a correlation for coal-fired plants given in the literature and an analysis of the relative amounts of power used in the fuel-handling system and the rest of the plant. The parasitic power for a wood-fired plant was found to be twice that for the coal-fired plant. The correlation found is:

$$P_{\text{para}} = 9.2 \text{ MW } (P_g/100 \text{ MW})^{0.86} \quad (\text{wood-fired plant}) \quad (\text{I-1})$$

where P_{para} is parasitic power and P_g is gross electrical power output.

In a similar fashion, cost correlations for large wood-fired plants were developed from correlations for installation cost, and operation and maintenance cost for coal plants available in the literature. The costs were broken down into those for the fuel-handling system and the rest of the plant. The costs for a wood-fired power plant were found to be

20 percent higher than those for a coal-fired plant of the same size. On this basis, cost equations for large-sized wood-fired power plants are as follows:

$$\text{Installation cost (1976 dollars)} = 47.9 \times 10^6 + 468 P_g \text{ (kW)} \quad (\text{I-2})$$

$$\text{Operation and maintenance cost (1976 dollars)} = 1.96 \times 10^6 + 2.66 P_g \text{ (kW)} \quad (\text{I-3})$$

Installation costs for smaller-sized wood-fired power plants were furnished by Mr. S. Hunter W. Brooks, a consulting engineer on the project. Analysis of these cost data yielded the following correlation for smaller sized wood-fired plants:

$$\text{Installation cost (1976 dollars)} = 18.7 \times 10^6 + 806 P_g \text{ (kW)} \quad (\text{I-4})$$

Equations I-2 and I-4 for installation costs for wood-fired power plants yield the same cost at a power output of 86,400 kW. Hence, equation I-2 is used for installation costs of power plants producing 86,400 kW or more and equation I-4 is used to calculate installation costs for power plants producing less than 86,400 kW. Using the above equations as a basis, the model calculates the cost per unit of electricity by each of two financing methods--the utility method and the municipal method.

At each of the 15 selected PEF sites, an average cost, delivery rate and moisture content of Energy PlantationTM fuel for the optimum-sized plantation was determined from the results of the Energy PlantationTM model calculations. These values were then fed into the power plant model, with which the performance of the power plant and the cost of electricity generated by the power plant were calculated. The power plant load factor at each site was determined by examining published data for the utility serving that site. Thus, the generator output calculated for each site corresponds to the required capacity of a power plant operating under the given conditions of yearly fuel supply and load factor.

For each site both a "low-performance" steam cycle and a "high-performance" steam cycle were analyzed. The low-performance cycle is considered to represent present-day wood-burning boiler technology. This is a simple Rankine cycle with steam supplied at a pressure of 650 psia and a temperature of 750°F, and a turbine having an efficiency of 79 percent. The high-performance cycle is considered representative of what could be accomplished with higher performance equipment comparable to that used in utility power plant systems. This is an extraction cycle with steam supplied at a pressure of 2400 psia and a temperature of 1000°F, and a turbine having an efficiency of 90 percent. For both cycles, a moisture content of 20 percent (wet basis) was specified for the fuel leaving the dryer, and an exhaust gas temperature of 200°F was specified for the exhaust gas leaving the dryer. A steam condensing temperature of 125°F was specified, so that the cooling water could be heated to a high enough value (115°F) to be of benefit to the algae pond. The conditions of the combustion air supply were assumed to be 70 percent excess at a temperature of 70°F and a relative humidity of 45 percent (specific humidity of 0.007).

The more significant results of the calculations for all 15 sites are summarized in Table I-7. These results show costs ranging from 70 mills/kWh to 107 mills/kWh as calculated by the utility method of financing for electricity generated by the low-performance steam cycle. At the other end of the spectrum, the costs calculated by the municipal method of financing for electricity generated by the high-performance steam cycle range from 35 mills/kWh to 53 mills/kWh. The results show a significant correlation between electricity costs and load factor with the cost decreasing as load factor increases. It is evident that the power plant economics are generally more favorable at sites where higher load factors prevail.

The capacities of the above power plants are very small by utility standards. To examine the economy-of-scale effect of Energy PlantationTM

TABLE I-7: : SITE COMPARISON OF POWERPLANT PERFORMANCE
AND GENERATED ELECTRICITY COSTS

Site	Load Factor (percent)	Delivered Fuel Cost (1976 dollars/oven-dry ton)		Cycle*	Generator Capacity(MW)	Cycle Efficiency (percent)	Electricity Cost (1976 mills/kWh)	
		Utility	Municipal				Utility	Municipal
		Method	Method				Method	Method
Bemidji, MN	48	22.10	16.90	L	57.7	17.5	78	52
				H	90.6	27.6	61	40
Caldwell, TX	43	27.73	19.99	L	70.1	17.3	86	56
				H	110.2	27.3	66	42
Chanute, KS	40	25.72	18.43	L	76.1	17.3	87	56
				H	119.5	27.3	66	42
Greenwood, SC	47	25.60	18.80	L	56.1	18.6	82	54
				H	88.0	29.5	64	41
42 Hammond, NY	46	24.83	18.95	L	64.9	18.8	79	52
				H	102.0	29.7	61	39
Jamestown, NY	68	26.05	19.45	L	41.6	18.3	70	48
				H	65.3	28.9	53	35
Kissimmee, FL	20	23.43	17.63	L	165.8	18.7	107	68
				H	260.4	29.5	87	53
Knoxville, TN	42	34.71	23.53	L	46.2	18.6	102	67
				H	72.6	29.4	79	50
Martinsville, VA	51	25.22	18.55	L	56.2	18.6	77	51
				H	88.2	29.5	60	39
Maysville, KY	76	33.95	23.55	L	25.2	18.0	86	58
				H	39.7	28.5	62	41
Minden, LA	34	26.25	19.17	L	95.3	18.4	90	58
				H	149.7	29.1	68	43
Natchitoches, LA	33	24.23	18.58	L	103.4	18.1	88	57
				H	162.4	28.6	67	43
Pensacola, FL	51	27.98	20.04	L	48.6	18.3	83	55
				H	76.3	29.0	64	41
Traverse City, MI	62	32.63	22.95	L	42.2	17.4	82	55
				H	66.2	27.5	62	40
Yazoo City, MS	39	25.84	19.01	L	67.1	18.3	90	59
				H	105.3	29.0	69	44

* L = low-performance cycle, H = high-performance cycle

produced electricity, different-sized "high-performance" power plants were analyzed at one location where an intermediate electricity cost prevails, viz., Natchitoches, Louisiana. The resulting costs show a marked economy-of-scale effect, with "utility-method" costs dropping from 67 mills/kWh at 160 MW capacity to 53 mills/kWh at 600 MW capacity and "municipal-method" costs dropping from 43 mills/kWh to 32 mills/kWh over the same range of generator capacities, and dropping slightly more to 31 mills/kWh at 1000 MW. Both costs show a slight tendency to increase as generator capacity increases above 1200 MW, with a more pronounced increase shown in utility-method costs. It is concluded that to take full advantage of the economy of scale, the power plant should have capacity of at least 500 MW. These results are plotted in Figure I-4 along with the estimated costs involved in generating electricity from coal at fuel costs of \$1.00 and \$1.50 per million Btu.

The costs of electricity generated from new coal-fired power plants at Natchitoches, Louisiana, were estimated with the power plant model--with appropriate changes to represent coal--for comparison with the costs of PEF-generated electricity. The results showed that these costs are comparable, particularly in the case of a PEF owned and operated by a municipality or some other governmental entity. This comparison, being done with the same model, eliminates any bias which may affect a comparison of cost estimates from different sources.

To examine the effects of changing certain controllable conditions on the performance of the power plant, a sensitivity analysis was performed for the low-performance cycle on the following parameters: (1) moisture content of delivered fuel and dry fuel, (2) temperature and pressure of steam produced by the boiler, (3) isentropic turbine efficiency and (4) excess air supply. The results of the moisture-content analysis show that performance is essentially independent of dried-fuel moisture content, except for the cases where no drying is done. The reason for the decrease in performance for the no-drying cases is that the screened-out fuel fines are not utilized, hence their heating value represents a net energy loss to the power plant. There is a significant increase in performance with a decrease in delivered-fuel moisture content from 50 percent down to 20 percent. With a further decrease in delivered-fuel moisture content, little or no increase in performance is noted.

FIGURE I-4 FUEL AND ELECTRICITY COSTS FOR WOOD-FIRED POWER PLANT AT NATCHITOCHES, LA., AND AVERAGE ELECTRICITY COSTS FOR COAL-FIRED POWER PLANTS VS. GENERATOR CAPACITY

3. PEF System Performance and Potential

The subsystem models which compose the comprehensive techno-economic PEF model were exercised for the fifteen potential demonstration sites. The results of these site analyses for the three subsystems, which were calculated with the single subsystem models operating independently, were combined to show what a complete demonstration PEF will look like and to illustrate the magnitude of the interactions within a PEF at a site. Table I-8 lists the important characteristics of a complete PEF demonstration project at each site being considered. For the algae pond, the table shows the characteristics of an algae pond subsystem designed to produce algae up to the carbon limit in the wastewater. In the discussion of the algae pond subsystem, it was shown that, at the present time, it is not cost-effective to design the algae pond to produce algae up to the phosphorus limit, with carbonation. Such a system may be cost-effective in the future with development of appropriate technology and only a moderate reduction in cost. The algae pond in the PEF at each site was sized to handle the wastewater flow from each population center, and the Energy PlantationTM was sized to produce solid fuel at an optimally low cost. This ratio of algae pond area to Energy PlantationTM area or rather wastewater flow to production of biomass is an important quantity which determines the extent of the influence of the algae pond upon the Energy PlantationTM.

Table I-8 shows the amount of SNG which can be produced by the algae pond system at each potential site. These quantities of gas are relatively small compared to the total market for gas at each site. The economic optimum for the size of an Energy PlantationTM unit, in terms of the cheapest fuel produced, is from 24,000 to 36,000 acres. The estimated productivities of these demonstration Energy PlantationsTM vary from 4.1 to over 9 dry tons

TABLE 1-8

CHARACTERISTICS OF POTENTIAL DEMONSTRATION PEF'SCarbon-Limited Design of Algae Pond System

Site	Algae Pond			Energy Plantation TM				
	Wastewater		Gas	Fertilizer	Fertilizer	Productivity*	Production**	
	Flow MGD	Acres	Produced 10 ⁶ SCF/YR	Produced Tons N/YR	Purchased Tons N/YR			
					Acres	Tons/Acres-YR	10 ³ Tons (O.D.)/YR	
Kissimmee, FL	1.3	20	4.15	42.7	2941	36,000	7.06	262
Pensacola, FL	6.0	101	19.1	197.0	2058	24,000	8.00	198
Chanute, KS	1.1	22	2.65	27.1	3020	36,000	7.45	277
Maysville, KY	0.7	13	1.67	17.2	1731	36,000	4.12	153
Natchitoches, LA	1.8	40	5.75	59.1	3093	36,000	7.55	279
Minden, LA	1.5	34	4.8	49.2	2941	36,000	7.04	261
Traverse City, MI	1.8	38	2.87	29.5	2734	36,000	6.32	232
Bemidji, MN	1.1	21	2.04	21.1	2960	27,000	9.05	250
Yazoo City, MS	1.1	27	3.51	36.1	2351	36,000	5.62	209
Hammond, NY	1.5	54	3.18	32.8	2778	36,000	6.37	237
Jamestown, NY	4.0	144	8.5	87.6	2586	33,000	6.59	225
Greenwood, SC	2.1	46	6.71	68.9	2253	30,000	6.50	201
Knoxville, TN	17.0	487	54.2	558.1	1176	33,000	4.41	150
Caldwell, TX	0.36	6	1.15	11.8	3009	36,000	7.38	275
Martinsville, VA	2.5	62	7.98	82.1	2441	30,000	7.06	218

* Average based on above-ground biomass.

** Average annual sustained production includes contribution of root mass produced upon replanting.

TABLE I-8 (Continued)

	Load Factor Percent	Power Plant			
		Simple Cycle		Efficient Cycle	
		Capacity MW	Production 10^6 KWH/YR	Capacity MW	Production 10^6 KWH/YR
Kissimmee, FL	20	166	290.5	260	456.3
Pensacola, FL	51	49	216.9	76	340.7
Chanute, KS	40	76	266.7	120	418.8
Maysville, KY	76	25	168.1	40	264.0
Natchitoches, LA	33	103	298.9	162	469.4
Minden, LA	34	95	283.8	150	445.7
Traverse City, MI	62	42	229.1	66	359.8
Bemidji, MN	48	58	242.6	91	381.0
Yazoo City, MS	39	67	229.1	105	359.9
Hammond, NY	46	65	261.6	102	411.0
Jamestown, NY	68	42	247.8	65	389.2
Greenwood, SC	47	56	230.8	88	362.5
Knoxville, TN	42	46	170.0	73	267.1
Caldwell, TX	43	70	264.4	110	415.2
Martinsville, VA	51	56	251.0	88	394.2

per acre-year.

Table I-9 shows the economics of a demonstration PEF at the potential sites under the assumption of municipal financing. The table shows the capital costs for the three PEF subsystems as well as the annualized costs. The annualized cash flow from the algae pond is a positive cash flow resulting from the applicable wastewater treatment credit rather than a cost. The cost of electricity produced from the power plant is shown before and after the wastewater treatment credit is applied to reduce the overall cost of operating the entire PEF. For sites such as Knoxville and Pensacola, which have the largest ratio of algae pond area (dependent upon available wastewater) to Energy PlantationTM area, the reduction in electricity cost can be significant. For the more efficient power plant, the cost of electricity, with the credit applied, of 40 mills per kilowatt-hour or so, should be attractive to rural areas, which are now paying the highest rates for electricity transmitted over a large distance from a large central power plant operated by a large utility.

One important interaction between the algae pond system and the Energy PlantationTM in a PEF is the contribution of fertilizer from the algae pond. Table I-10 presents data which illustrate this interaction in detail, both with present technology in operating a carbon-limited algae pond and with future technology in operating a phosphorus-limited system. This table shows the amount of nitrogen fertilizer produced by the algae pond at each site and the resultant reduction in cost of biomass produced, the fertilizer being valued at its equivalent in ammonium nitrate. The reduction in the cost of biomass can be significant if there is sufficient wastewater, such as is the case at Knoxville and Pensacola.

TABLE I-9
ECONOMICS OF POTENTIAL DEMONSTRATION PEF'S

Carbon-Limited Design of Algae Pond System, Municipal Financing

Site	Algae Pond		Energy Plantation TM		
	Capital Cost \$10 ⁶	Total Annual Cash Flow* \$10 ⁶	Capital Cost \$10 ⁶	Total Annual Cost \$10 ⁶	Cost of Fuel \$/Ton (O.D.)
Kissimmee, FL	0.814	0.300	25.13	4.73	17.63
Pensacola, FL	2.279	1.602	5.27	4.06	20.04
Chanute, KS	0.786	0.150	31.39	5.10	18.43
Maysville, KY	0.592	0.027	23.29	3.75	23.59
Natchitoches, LA	1.100	0.421	7.34	5.28	18.58
Minden, LA	0.981	0.343	6.87	5.15	19.17
Traverse City, MI	1.087	0.131	8.81	5.32	22.96
Bemidji, MN	0.782	0.021	7.47	4.22	16.90
Yazoo City, MS	0.834	0.235	6.53	4.05	19.01
Hammond, NY	1.143	0.165	7.55	4.54	18.95
Jamestown, NY	2.155	0.374	7.10	4.48	19.45
Greenwood, SC	1.203	0.504	6.07	3.89	18.80
Knoxville, TN	5.883	4.619	5.76	3.72	23.53
Caldwell, TX	0.389	0.056	27.10	5.49	19.99
Martinsville, VA	1.395	0.612	6.18	4.21	18.65

* A positive cash flow, rather than an annualized cost, because of the wastewater treatment credit.

TABLE I-9 (Continued)

	Power Plant							
	Simple Cycle				Efficient Cycle			
	Capital Cost \$10 ⁶	Total Annual Cost, \$10 ⁶	Cost of Electricity \$/KWH	\$/KWH(with crd.)	Capital Cost \$10 ⁶	Total Annual Cost, \$10 ⁶	Cost of Electricity \$/KWH	\$/KWH(with crd.)
Kissimmee, FL	125.50	19.62	0.068	0.067	169.78	24.36	0.053	0.052
Pensacola, FL	57.83	11.91	0.055	0.048	80.16	14.14	0.041	0.036
Chanute, KS	80.04	15.01	0.056	0.055	103.84	17.46	0.042	0.042
Maysville, KY	39.05	9.69	0.058	0.058	50.67	10.84	0.041	0.041
Natchitoches, LA	96.29	17.10	0.057	0.056	123.90	20.00	0.043	0.042
Minden, LA	92.49	16.50	0.058	0.057	117.94	19.16	0.043	0.042
Traverse City, MI	52.69	12.56	0.055	0.054	72.09	14.49	0.040	0.040
Bemidji, MN	65.20	12.60	0.052	0.052	90.31	15.13	0.040	0.040
Yazoo City, MS	72.75	13.43	0.059	0.058	97.20	15.91	0.044	0.043
Hammond, NY	71.03	13.73	0.052	0.051	95.63	16.23	0.039	0.039
Jamestown, NY	52.23	11.81	0.048	0.047	71.37	13.72	0.035	0.034
Greenwood, SC	63.88	12.44	0.054	0.052	89.11	14.97	0.041	0.040
Knoxville, TN	55.95	11.32	0.067	0.040	77.21	13.44	0.050	0.033
Caldwell, TX	75.26	14.92	0.056	0.056	99.49	17.39	0.042	0.042
Martinsville, VA	63.98	12.78	0.051	0.049	89.20	15.31	0.039	0.037

TABLE I-10

CHARACTERISTICS OF ALGAE POND SYSTEMS IN A DEMONSTRATION PEF

Site	Wastewater Flow, MGD	Carbon-Limited Algae Pond			Reduction in Fertilizer Cost per Ton \$/Ton	Phosphorus-Limited Algae Pond			Reduction in Fertilizer Cost per Ton \$/Ton	Energy Plantation™ Purchased Fertilizer Tons N/YR
		Acres	Gas 10 ⁶ SCF/YR	Fertilizer Tons N/YR		Acres	Gas 10 ⁶ SCF/YR	Fertilizer Tons N/YR		
Kissimmee, FL	1.3	20	4.15	42.7	0.07	156	22.9	229.4	0.38	2941
Pensacola, FL	6.0	101	19.1	197.0	0.43	789	106.0	1058.8	2.31	2058
Charute, KS	1.1	22	2.65	27.1	0.04	175	14.7	145.6	0.21	3020
Maysville, KY	0.7	13	1.67	17.2	0.04	103	9.3	92.6	0.22	1731
Natchitoches, LA	1.8	40	5.75	59.1	0.08	317	31.9	317.6	0.43	3093
Minden, LA	1.5	34	4.80	49.2	0.07	264	26.6	264.7	0.38	2941
Traverse City, MI	1.8	38	2.87	29.5	0.05	300	15.9	158.8	0.27	2734
Bemidji, MN	1.1	21	2.04	21.1	0.03	167	11.3	113.2	0.16	2960
Yazoo City, MS	1.1	27	3.51	36.1	0.07	212	19.4	194.1	0.38	2351
Hammond, NY	1.5	54	3.18	32.8	0.07	422	17.6	176.5	0.38	2778
Jamestown, NY	4.0	144	8.5	87.6	0.19	1127	47.1	470.6	1.02	2586
Greenwood, SC	2.1	46	6.71	68.9	0.15	359	37.1	370.6	0.81	2253
Knoxville, TN	17.0	487	54.2	558.1	1.60	3806	300.0	3000.0	3.37	1176
Caldwell, TX	0.36	6	1.15	11.8	0.02	51	6.4	63.5	0.11	3009
Martinsville, VA	2.5	62	7.98	82.1	0.16	482	44.2	441.2	0.86	2441

The results of the model calculations are useful in evaluating and ranking potential sites for a demonstration. Some important attributes of sites for a potential demonstration are low cost--both capital cost and operating cost. Other attributes are the magnitude of the fertilizer contribution--the higher, the better to demonstrate this important PEF interaction--and the difference in cost of the electricity produced by the PEF and the current local cost--the smaller this difference, the sooner the demonstration will be cost-effective. The overall rank was determined simply by adding up the ranks of the four separate attributes and listing the sites in terms of ascending value (but decreasing rank). For further, more detailed consideration of a suitable site for a demonstration PEF, the top five sites should be included in the analysis. These are: Pensacola, FL; Jamestown, NY; Knoxville, TN; Martinsville, VA; and Greenwood, SC.

The overall objectives of a PEF Demonstration Project would be to demonstrate the economics and technology of growing plant matter purposely for its fuel value on a large scale according to the Energy PlantationTM and PEF concepts, and of using this plant matter to generate electricity which can be introduced in a reliable fashion into a utility power grid. Although current or near-term technology is involved in all parts of the Energy PlantationTM, plant matter has never been produced in this fashion for the purpose of producing fuel, and the actual economics have never been demonstrated. Although the Energy PlantationTM appears to be economically viable in the near term, reservations do exist about some of its features which are unique, and these reservations, which prevent widespread implementation of the concept, can be resolved with a demonstration project.

The objectives of demonstrating the algae production subsystem of PEF are more oriented toward research and development. The technology of some of the parts of this subsystem is far from being developed or

proven, and the economics of the algae production subsystem are less certain now than the economics of the Energy PlantationTM. Thus, the algae subsystem will be designed with the idea of using it to develop and to prove the technology, by doing critical experiments and revising the system as data are obtained.

The analysis which has been performed so far indicates that some interactions between the PEF subsystems are generally cost-effective while others are probably site-specific or can be improved upon. However, various improvements may be made both in the model and in the analysis of the applicability of PEF. In the present work, for example, neither the potential irrigation of the Energy PlantationTM with reclaimed wastewater nor the heating of the algae pond was considered. These potential interactions of the PEF subsystems should be studied to extend the synergy of the concept. Furthermore, the current model has been developed to include conventional technology available today. The model should be expanded and refined to include near-term technology to represent more accurately the potential of the PEF concept.

Most of the experimental data used in determining the growth parameters of the species of interest for Energy Plantation application were generated on nonirrigated plots (a list of the original data base is given in the references to Appendix C). As was mentioned earlier, the productivities derived from the model, as well as the potential application of the PEF model, is thus only valid for sites where sufficient rainfall is available to sustain growth at the production levels considered (eastern part and some regions of the western United States). Some data indicate that even in regions where total rainfall during the growing season is sufficient to sustain the average annual yields estimated from the experimental data, irrigation may be beneficial by reducing moisture stress during periodic drought periods occurring during the growing season (49).

Irrigation of the Energy Plantation is thus an important possible extension of the PEF concept which has several ramifications. First of all, scheduled irrigation during the growing season in regions with sufficient average

rainfall to sustain predicted yields could improve plantation yields by reducing moisture stress during the growing season. Second, irrigation of the Energy Plantation with reclaimed wastewater from the algae pond would allow the PEF concept to be implemented at locations naturally too dry for an Energy Plantation by itself. Third, irrigation could possibly improve the use of fertilizer by allowing it to be distributed onto the plantation whenever it is needed, annually, rather than in one large dose at harvest time. Finally, an irrigation system could also be useful in allowing wastewater to be applied directly (after primary sedimentation) to the dry-land Energy Plantation. Viewed in a larger perspective, the Photosynthesis Energy Factory is a bioconversion system which integrates material and resource recycling with biomass production for fuel.

The synergy inherent in the overall PEF concept can be preserved with direct application of wastewater to the Energy PlantationTM. The nutrients such as nitrogen and phosphorus are made available to the growing plants. Water is recycled in a useful way. The wastewater treatment credit, which is the most important economic benefit of the algae pond to the PEF, would apply to the Energy PlantationTM directly, helping to pay for the irrigation system and to lower the cost of the biomass produced. As for recycle of the carbon dioxide evolved from the power plant, our analysis indicates that with current technology, carbonation of algae ponds to increase the yield of algae from wastewater by tying up nitrogen and phosphorus, is not cost-effective at the present time. At the present time, no data exist that show any increase in productivity of algae ponds (tons per acre-year) due to carbonation.

Our estimated energy balances show that the net energy recovery per acre-year (gross energy yield less needed energy input, without energy conservation credits) for the Energy PlantationTM (about 130×10^6 Btu per acre-year based on eight tons production less five percent) is about twice that for the algae pond (about 66×10^6 Btu per acre-year, based on ten tons production). The Energy PlantationTM thus recovers energy more efficiently than the algae pond. In addition, the Energy PlantationTM does not need special carbonation equipment to utilize carbon dioxide in the air (flue

gas); it does so naturally. Thus, for growing biomass by utilizing the carbon dioxide in flue gas, an acre of dry-land Energy PlantationTM produces greater energy yield than an acre of algae pond at significantly lower cost, with present technology.

Of course, the energy from an algae pond system is in the form of SNG, which is more desirable as a fuel than the solid fuel from an Energy PlantationTM. However, the SNG from a recarbonated algae pond is costly, according to our current estimates, and technology and cost reduction innovations are necessary. The potential exists, according to University of California at Berkeley, for increasing the productivity and hence the energy recovery, from an algae pond system. Doubling the productivity from 10 to 20 tons per acre-year would increase the net energy yield from 66 to 166 million Btu per acre-year in the form of SNG, and this is certainly a desirable goal which should be pursued.

However, the alternative to including the algae pond in the PEF, viz., direct land application of wastewater, appears to have significant advantages and should be analyzed in parallel with the algae pond in later projects to develop the PEF concept further. Further work should be done to define the possible improvements in algae pond technology which can be brought to bear on the PEF concept. The economics of the PEF concept can be improved significantly if ways can be found to improve the efficiency of using Energy PlantationTM biomass as a solid fuel.

Overall, the results of this first project in analyzing the usefulness of the PEF concept show that there is value in some of the interactions which are possible in a PEF system. The results also indicate where potential exists for improving the concept, and these indicated approaches should be explored to develop the Photosynthesis Energy Factory into a more cost-effective alternate energy source and energy recovery system.

D. Conclusions

Site-Screening Procedure

1. The site-screening procedure turned up a number of potential sites which would apparently be suitable for a demonstration PEF, but the final choice is influenced significantly by local site-specific factors which would be difficult to evaluate except in a very detailed fashion. Fifteen sites were selected for analysis with the PEF techno-economic model.

Energy PlantationTM Model

2. As the result of applying the Energy PlantationTM techno-economic model to the fifteen sites selected for analysis of the PEF concept, the following general conclusions were reached:
 - a. Depending on the sites, plantations on the order of 24,000 to 36,000 acres are recommended to produce biomass at lowest cost per ton.
 - b. At the most favorable sites, biomass can be produced and delivered for \$17 to \$20/oven-dry ton (municipal financing), on a sustained basis.
 - c. At the most favorable sites, the plantation capital cost is of the order of \$25 to \$30/oven-dry ton-year, or about \$7 million for a typical plantation.
 - d. The energy required to operate the plantation and produce the nitrogen fertilizer needed amounts to 3 to 5 percent of the plantation energy output.
3. Comparison of the sites on the basis of cost of biomass, investment required, and energy efficiency suggests Natchitoches, Louisiana; Minden, Louisiana; Greenwood, South Carolina; and Pensacola, Florida, as potential demonstration sites.
4. A sensitivity analysis of the data for a base case (Natchitoches, Louisiana, site) shows that:
 - a. With pneumatic tube transportation of the wood chips, the cost of biomass remains essentially constant with plantation size ranging from 30,000 acres to several hundred thousand acres.

- b. Absolute sustained yield (oven-dry ton/acre-year) is not the major factor in determining the cost of biomass. All other conditions being equal, fluctuations in yield amounting to about 20 percent result in changes in cost of 9 to 10 percent. Due to climatic fluctuations, variations in cost of that order of magnitude can thus be expected.
- c. Planting and harvesting cycles and the number of coppice harvests are important parameters which influence strongly the economics of the plantation. Maximum yield does not necessarily imply lowest cost, which is the more important parameter.
- d. Fertilization is a major component of operating cost.
- e. Preliminary data indicate that there are some interactive effects on cost from several plantation parameters. Such is the case with the size of parcels that compose the plantation, and plantation density, which can have opposite (and compensating) effects on the cost of biomass.

Algae Pond Model

- 5. The predicted annual production of algae per acre of pond for the candidate sites ranged from 4.64 to 16.32 tons of dry algae per acre per year. Current bench- and pilot-scale experiments have achieved short-term yields equivalent to 30 tons per acre per year, indicating that increases in mass culture yields are perhaps feasible with proper pond operation and careful control.
- 6. Using currently available technology, a carbon-limited algae system could provide cost-effective secondary wastewater treatment compared to a conventional activated sludge system. A 1-MGD (base case) system of this type would require 25 acres of high-rate growth ponds. The system would produce 3.18×10^6 SCF of SNG and 32.8 tons of nitrogen annually. Combining SNG production and energy conservation credits for wastewater treatment and fertilizer production, the pond system has a net energy production density of 160 million Btu per acre-year.

7. Using only conventional or near-term technology, the most cost-effective algae pond for a PEF is the carbon-limited secondary treatment system. This system does not recycle CO_2 from the flue gas. Both carbon- and nitrogen-limited systems are less costly than comparable activated sludge operations.
8. Cost-effective expansion of the algae pond to allow treatment up to the phosphorus-limit production of SNG is contingent on the development of the operational ability to maintain nitrogen-fixing algal populations, and on a 25-percent cost reduction innovation in process design. A phosphorus-limited algae system could provide tertiary treatment of wastewater. A 1-MGD system would produce 1.76×10^7 SCF of SNG and 176.5 tons of nitrogen annually. At the currently assumed conversion efficiency, the system would require 193 acres of pond and have a net energy production density of 107 million Btu per acre-year. If a 50-percent increase in conversion efficiency could be realized, the required pond acreage would drop to 129 acres. This system would then have a net energy production density of 170 million Btu per acre-year.
9. Three major influences on cost-effectiveness of algae ponds are:
 - (1) Plant design flow rate (economy-of-scale effects),
 - (2) Months of operation annually, and
 - (3) Level of treatment required and the value of the credit for that level of treatment.
10. Pond construction is the largest element in the capital cost and accounts for 30 percent of the total annualized cost of the systems.
11. The wastewater treatment credit for the carbon-limited algae pond is 98 percent of its total credit, and 93 percent for a phosphorus-limited system. The remaining credit is for the gas produced.

Power Plant Model

12. The most economical conditions for a wood-fired power plant are a high-pressure and high-temperature steam cycle at a capacity of 500 to 1000 MW, and a high load factor. In this range of capacity, the cost of electricity is 32 to 31 mills/kWh (municipal financing). These conclusions are as expected, since they reflect the well-known experience with similar coal-fired steam-generating power plants. At the present time, however, such a large wood-fired power plant must be custom-designed since such technology is not off-the-shelf.
13. The presence of water in the fuel effects a significant reduction in power plant performance at a level of 20 percent or more. The performance of the power plant could be improved if the fuel could be predried before entering the power plant or if some way could be found to recover the latent heat of the water vapor in the flue gas.
14. The performance of the power plant is significantly affected by the amount of excess air supplied. It is therefore worthwhile to include a monitoring system in the power plant that will allow the air supply rate to be kept at the minimum level necessary to permit essentially complete combustion.
15. The cost of electricity generated in a PEF is comparable to the cost of electricity generated in a new coal-fired plant, particularly if the PEF is owned and operated by a municipality or some other governmental entity.

PEF Model

16. Considering the characteristics for a suitable demonstration PEF of low capital and operating costs, the magnitude of the contribution of fertilizer from the algae pond, and a low difference in present cost of electricity and PEF-generated electricity, the following potential sites are recommended for more detailed evaluation: Pensacola, Florida; Jamestown, New York; Knoxville, Tennessee; Martinsville, Virginia; and Greenwood, South Carolina.

17. Development of the necessary technology to make a phosphorus-limited algae pond system feasible and cost-effective would enable the algae pond to increase its fertilizer production to over five times that of a carbon-limited system.
18. With ordinary municipal wastewater, a carbon-limited algae pond system operating the year around can provide about 2.9 percent (32.8 tons nitrogen per year) of the total annual nitrogen fertilizer requirement for 100,000 oven-dry tons of annual production per MGD of wastewater flow; this fertilizer contribution lowers the cost per ton of biomass about \$0.15.
19. The cost of electricity which could be produced from a PEF at the potential sites evaluated was in the range of 33 to 52 mills per kilowatt-hour (municipal financing) for a power plant utilizing the estimated high-performance cycle with a capacity of 40 to 160 MW (load factor varies from 20 to 76 percent). Although these costs are currently higher than current costs of fossil-fuel-generated electricity--because of higher fuel-handling costs and lower power generation efficiency--such may not be the case in a few years, particularly on a life-cycle basis. A demonstration should be planned now and implemented so that the technology will be ready when needed.
20. With a carbon-limited algae pond system, the annual credits for wastewater treatment and gas production -- the former being by far the most significant credit -- exceed the annualized cost of the algae pond system, and the excess credit applied to the annualized cost of the power plant enables the cost of electricity to be reduced by 1.6 to 2.5 mills per kilowatt-hour for the electricity produced from 100,000 tons of biomass per MGD of municipal wastewater flow.
21. Waste heat from the power plant, used to heat the anaerobic digester in the algae pond system, should enable the net gas production to double in contrast to the case where part of the gas itself is used to heat the digester.

E. Recommendations

1. The Energy PlantationTM model should be extended to include modeling for irrigation. Inclusion of irrigation in the model would allow several significant impacts to be analyzed:
 - a. Irrigation would permit the PEF to be implemented in regions naturally too dry for an Energy PlantationTM by itself. Irrigation would then extend the area of applicability of the PEF concept.
 - b. Irrigation could possibly improve the use of fertilizer by allowing it to be put onto the plantation whenever it is needed, annually, rather than in one large dose at harvest time which would undergo degradation and loss over a period of several years.
 - c. An irrigation system could also be useful in allowing wastewater to be applied directly (after primary sedimentation) to the Energy PlantationTM, thereby achieving some of the interaction (nutrient recovery) between the Energy PlantationTM and the algae pond at possibly lower cost and enabling the wastewater treatment credit to be applied to the Energy PlantationTM.
2. Other work should be done with the Energy PlantationTM model to investigate further optimization of transportation of the biomass and local in-the-field storage. More detailed analysis of the tube transport system should be done.
3. At present, nutrients are applied to the Energy PlantationTM at the level required to maintain plantation productivity. The impact of yield-boosting through supplementary fertilization has not been examined. More efficient methods of application of fertilizer or the use of nitrogen-fixing crops should be examined.

4. Further sensitivity analyses should be done to examine interactive effects of plantation parameters and optimization of fertilizer application and use.
5. A few sites should be examined (preferably those with 12-month operation and 5-MGD flow) to analyze competing waste treatment options such as stabilization ponds, land application including their sludge disposal problems. Site-specific waste treatment credit should be determined and the benefit and impact of a PEF at these sites then recomputed.
6. The medium-term potential for significant cost reduction in pond construction, and process equipment costs should be analyzed. Based on results obtained, incremental costs of gas produced should be recomputed to determine whether to go beyond the carbon-limited design.
7. Where the potential of a phosphorus-limited design is reasonably close to being cost-effective, a demonstration site could be selected for which land would be available for a phosphorus-case expansion. Pond and carbonation equipment should be installed to obtain operational experience with pond carbonation.
8. Experimentation with mass-culture species-control should be supported.
9. Other approaches to using algae beside digestion should be investigated-- for example, dewatering and direct combustion, production of chicken feed, and dewatering and land application of algae.
10. Ways of using biomass as a solid fuel more efficiently should be examined:
 - a. Biomass could be used as a solid fuel in admixture with coal;
 - b. Costs of building a high-efficiency wood-fired power plant, possibly with different types of combustion equipment, could be investigated; and
 - c. Ways of either getting water out of fuel before combustion or

recovering and using latent heat of water vapor in flue gas should be studied.

11. The application of PEF at various types of sites using local site-specific data to refine the evaluation of PEF should be analyzed in detail.

II. SELECTION OF POTENTIAL SITES FOR A DEMONSTRATION PEF

A. General

The goal of the project task concerned with site selection was to identify potential sites for a demonstration PEF for consideration in the demonstration design task. Thus, in the site-selection task, a multitude of sites was considered to pick a few sites where the necessary resources could be found to mount a successful PEF demonstration. The sites selected as a result of the work of the site-selection task were then further evaluated with the PEF techno-economic model to determine the potential benefits of a PEF demonstration. Because it was realized that local site-specific factors such as the degree of local participation could be the most crucial determinants of the suitability of a site for a demonstration, the final determination of a demonstration site cannot be made until these local factors can be evaluated in greater detail. This requires an in-depth effort which was beyond the scope of this project.

The overall goal of the site-selection task was accomplished by means of two subtasks. The first subtask was to develop an appropriate site-selection procedure, and the second was to use the procedure to screen potential sites to select candidates for further evaluation with the PEF model.

B. Development of the Site-Screening Procedure

The objective of this work was to develop a methodology which, when applied to various sites, could evaluate sites according to the available necessary resources for the establishment and use of a PEF. The first step in developing this methodology was to identify what resources are needed for a PEF. The second developmental step was to devise the appropriate screening procedure.

1. Inventory of Resources and Services

All resources and services which are needed at a site for a PEF were assembled.

These site characteristics could be conveniently grouped into three artificial categories--the physical environment, raw materials and resources, and market for PEF products and services. These site characteristics are shown in Table II-1.

a. The Physical Environment

Climatic factors influence the operating characteristics of both the algae pond and the Energy PlantationTM. Rainfall is necessary for growing woody biomass on the Energy PlantationTM. The length of the growing season, as dictated by ambient temperature, and the temperature itself affect the productivity of both plantation and pond. The energy harvested from pond and plantation is a fraction of the total insolation. The type of soil at the Energy PlantationTM site dictates the operations that the plantation site will withstand, the moisture and nutrients available to the energy crop, and the recycling characteristics of sludge from the algae pond. The soil also affects the construction of the algae pond.

b. Raw Materials and Resources

The amount of energy that can be recovered is proportional to the land that is available for plantations. The topography of the land will determine the type of construction necessary to build algae ponds. Forestry residues and dry organic wastes from municipalities, industry, and farming can be used as a supplemental fuel for the boilers. Nontoxic, high-BOD wastes can be used to grow algae. An auxiliary source of cooling water will be needed as a standby to the process use of waste heat. People will be needed to run the PEF.

c. Market for PEF Products and Services

The main product of the PEF is fuel. The fuel produced may be used as electricity, steam, and synthetic natural gas with a range of Btu depending on the intended use and economics thereof. The use of cull forest residues

TABLE II-1

PEF SITE DESCRIPTION

I. Physical Environment

A. Climate

1. Rainfall Pattern
2. Temperature Profile
3. Insolation

B. Soil

1. Soil Moisture Profile
2. Particle Size, Matrix

II. Raw Materials and Resources

A. Land Availability and Capability

B. Forestry Raw Materials

C. Wet Organic Effluents

1. Sewage
2. Industrial
3. Farm Wastes

D. Dry Organic Resources

1. Municipal Solid Waste
2. Industrial Solid Waste
3. Farm and Forestry Wastes

E. Sources of Cooling Water

F. Labor Pool

III. Market for PEF Products and Services

A. Energy

1. Electricity
2. Steam
3. Low or High Btu Gas

B. Use of Cull Trees

C. Need for Waste Treatment of All Kinds

D. Need for Jobs

allows the forest industry to derive a credit for clearing noncommercial woodlands for commercial development. Through the PEF, a number of wet and dry organic residues can be disposed of. The PEF will provide jobs and keep dollars spent on energy in a local economy.

2. Development of Quantitative Indexes

The PEF site characteristics listed in Table II-1 are all necessary data in the evaluation of a PEF system at a particular site, but some of these characteristics are more influential than others in discriminating between sites in a site-screening procedure. Particularly influential are the site characteristics relating to land availability and capability. Because one of the major objectives of a demonstration project would be to demonstrate the feasibility and the economics of the Energy PlantationTM subsystem which would be strongly influenced by land characteristics, quantitative indexes were considered to evaluate land characteristics at potential sites.

Four indexes chosen to represent land characteristics at potential sites were: (1) available acreage of suitable land; (2) suitable land density; (3) suitable land capability, and (4) relative value of suitable land.

a. Available Acreage

Prior research (6) has shown that land that is only marginally suited to intensive agricultural use or land that is not used to its full potential could logically become available for use as biomass plantations. Thus, the county where the possible PEF site is located and counties surrounding that county in some cases were surveyed using the U.S. Soil Conservation Service Conservation Needs Inventory (8) to identify marginal or underused acres.* Surrounding counties were used in some cases when they fell within a 30-mile radius of the possible PEF site. The total available acreage was thus estimated for a possible site.

b. Land Density

The density of suitable acres in the total area at a site has been shown

* Available suitable land in this context means all land in classifications 4,6, and 7 and land in noncommercial forest and grazed commercial forest in 1,2, and 3. See reference 6 for further details.

to relate to the average size of individual plantation plots and the proximity of plots to one another (4). These factors influence the operation schedule of the plantation, hence the economics of operation. The density index is the total suitable acres divided by the total acres at a site.

c. Land Capability

The productivity of the various land capability classes (8) has been shown to relate to the investment required to farm each class of land (9). For example, if the same unit of investment or effort were applied to farming an average piece of cropland and a piece of land designated as marginal, the return on the marginal land would be about three-quarters of the return on average cropland. Thus, the values for this index compare the weighted average of all the suitable acres at a site with average cropland, which has the value 1.00.

d. Relative Use Value

In general, the value of farmland depends to a large extent on its relative productivity, which is quantified by the land capability index derived above. However, the absolute real-estate value of land depends on a number of factors, of which agricultural productivity is only one. The relative use value index for suitable plantation land at a site is a weighted average value calculated by combining the productivity values for the classes of land present at a site with the local cost of land. The value for the local cost of land at a site was taken from the 1974 cost reported in the Census of Agriculture (10).

3. Development of Qualitative Indexes

In addition to the availability of land for a biomass plantation, other resources and services are needed at a site for the establishment of a demonstration PEF. However, some of these other resources and services are difficult to quantify, or their quantification does not necessarily aid in discriminating between potential PEF sites. Thus, some of these other resources and services act more as constraints, to eliminate sites without them from consideration, but a greater or lesser amount of them, as

long as they are present, does not increase or decrease the relative desirability of a particular site.

For example, as long as the rainfall at a particular site is above the minimum amount needed to establish an Energy PlantationTM, how much more desirable is a site with, say, 10 more inches of rainfall annually than another site? It was decided that it would not be productive to try to derive a numerical site-ranking criteria, which would attempt to assign numerical values to these resources and services. Even if weighting factors were used to attempt to balance the weights of the various resources, weighting factors would be quite arbitrary and a matter of judgment, and combining the numerical factors to arrive at one number which would characterize the desirability of a site would be quite artificial.

Therefore, to recognize the importance of some of these unquantifiable resources and services, their presence or absence at each site is simply noted. The desirability of a particular site must, therefore, be considered a matter of judgment on the basis of the whole body of data and information. The resources and services considered as part of this qualitative analysis are:

- (1) Market for electricity.
- (2) Market for SNG.
- (3) Sufficient rainfall for an Energy PlantationTM.
- (4) Labor for operating the PEF.
- (5) Alternate source of dry residues for supplementing the fuel to the boiler.
- (6) Wet organic residues as additional input to the algae pond.
- (7) Cooling water for the power plant.
- (8) Possible local participation in a PEF project.

Of these factors, possibly the most important for the purposes of siting an ERDA-sponsored demonstration PEF project--aside from sufficient rainfall--is the possibility of local participation in a PEF project, and it is not possible to quantify this factor at the present time.

4. Evaluation of the Screening Procedure

The screening procedure outlined above, consisting of quantitative and qualitative indexes, was tested for its discriminatory powers. Data were assembled and analysis performed for some 70 sites in the eastern United States. These 70 sites were picked originally by applying three constraints:

1. There was adequate rainfall for woody biomass crops.*
2. There was information to support our choice of at least one biomass crop.
3. We could see a need for additional local electrical generating capacity on the part of a local rural or municipal electric cooperative.

The first conclusion to be drawn was that there was no one or a few sites that were obviously better relative to the remainder. When the 70 sites were ranked in the four quantitative categories from best to worst, over half of the sites had to be screened in each category to find one site which appeared in all four categories.

The site identified in all four categories--Jamestown, New York--was then compared index by index with other sites whose indexes were at least as good as, or better than, any three out of these indexes for Jamestown. Two groups of sites were identified. For one group, the land capability class was lower; Yazoo City, Mississippi, and Chanute, Kansas, are examples of this group. The use value was higher for the second group of sites, indicating that the use of those sites would be comparatively more expensive to obtain. The second group of sites included Kissimmee, Florida; Natchitoches, Louisiana; and Minden, Louisiana. The sites discussed here are shown in Table II-2.

The second conclusion was that the qualitative indexes were important to the screening procedure, particularly public participation.

* Adequate rainfall for woody biomass crops means more than 20 inches per year.

TABLE II-2
SITE SELECTION TEST

<u>Qualitative Screening</u>								
<u>Site</u>	Participation	Cooling Water	Labor	Demand for Electricity	Demand for Gas	Dry Residues	Wet Residues	Rainfall
Kissimmee, FL	0	+	0	+	+	0	0	+
Chanute, KS	0	0	0	+	+	+	+	+
Natchitoches, LA	0	+	0	0	+	+	+	+
Minden, LA	0	+	0	+	+	+	+	+
Yazoo City, MS	+	+	+	+	+	+	+	+
Jamestown, NY	0	+	+	+	0	+	+	+

Quantitative Screening

<u>Site</u>	Suitable <u>Acres(1000's Acres)</u>	Land <u>Density</u> ¹	Land <u>Capability</u> ²	Use <u>Value</u> ³
Kissimmee, FL	523.26	0.62	0.77	317
Chanute, KS	220.59	0.21	0.54	166
Natchitoches, LA	413.54	0.51	0.79	444
Minden, LA	308.66	0.37	0.79	448
Yazoo City, MS	178.98	0.30	0.64	224
Jamestown, NY	150.77	0.20	0.74	305

+ = Positive indication of supply of resources or demand for service.
0 = Uncertainty surrounding supply of resource on demand for service.

¹ Suitable acres divided by total acres at site.

² Weighted average productivity of suitable land at site relative to average cropland, which has a value of 1.00.

³ Weighted average value of suitable land at site.

Local groups could influence the availability of a given resource or use of a given service. This fact made it imperative that local agencies be contacted.

C. Site-Screening Procedure

The objectives of this work were to gather data on a large number of sites and to show that few of those sites offered the right mix of inputs and outputs necessary for the successful demonstration of the PEF. The first step in this procedure was to gather data from local sources. The second step was to reduce the collected data by the screening procedure to identify potential demonstration sites which would be worthy of further consideration and analysis in the next project phase based on site-specific data obtained locally.

1. Contact with the State Energy Offices

Inquiries were sent to the energy office, land planning office, and power plant siting office of each of the 48 conterminous states. These letters were sent to several offices in the same state because it was not known beforehand which office would have the desired data; data would perhaps be needed from all three types of offices. The questions asked were purposely general in tone to elicit opinion as well as statistical fact. The site survey information sheet sent to the state offices is shown in Table II-3. The names and addresses of the agencies queried are listed in Appendix E. The 41 states which responded are listed in Table II-4.

2. Sites Identified From State-Supplied Information

From the responses, at least one site which superficially met our selection criteria was identified in every state. Sites identified through analysis of state-provided information are listed in Table II-5

TABLE II-3
SITE SURVEY INFORMATION SHEET
FOR THE
PHOTOSYNTHESIS ENERGY FACTORY

1. Land Resources - In which counties is land less suitable for the production of agricultural crops, or overall farm profit per acre is low?
2. Unusable Forest Resources - In which counties do, for example, forest areas contain a large fraction of hardwoods and nearby forest product industries use softwoods?
3. Cooling Water - Which flowing bodies of water will the current environmental quality standards permit use as a source of cooling water?
4. Nutrient-Rich Effluents - What are the locations of potential supplies of nontoxic, high BOD (biological oxygen demand) nutrient-rich effluents, such as from dairy products processing or beef feedlots?
5. Dry Residues - What are the locations of potential supplies of dry cellulosic residues, such as forest and farming crop residues, and the like?
6. Available Labor^{*} - In which counties is there high unemployment in the construction trade?
7. Market for Electricity - In which counties are there potential users of electric power, such as an electric cooperative which purchases part of the power it sells or an industry which generates some of the electricity it uses?
8. Market for Synthetic Natural Gas - In which counties are there potential industrial users of synthetic natural gas?

* The construction trade was specifically mentioned because it would be representative of the labor skills necessary to operate the PEF.

TABLE II-4
STATES RESPONDING TO SURVEY

Alabama
Arizona
Arkansas
California
Connecticut
Delaware
Florida
Georgia
Illinois
Indiana
Iowa
Kentucky
Louisiana
Maine
Maryland
Massachusetts
Michigan
Minnesota
Mississippi
Missouri

Montana
Nebraska
New Hampshire
New Jersey
New Mexico
New York
North Carolina
North Dakota
Ohio
Oklahoma
Pennsylvania
Rhode Island
South Carolina
South Dakota
Tennessee
Texas
Virginia
Washington
West Virginia
Wisconsin
Wyoming

TABLE II-5
SITES IDENTIFIED FROM STATE-PROVIDED INFORMATION

<u>City</u>	<u>County</u>	<u>State</u>
Andalusia	Covington	Alabama
Globe	Gila	Arizona
Fayetteville	Washington	Arkansas
Sacramento	El Dorado	California
Delmar/Seaford	Sussex	Delaware
Gainesville	Alachua	Florida
Washington	Wilkes	Georgia
Springfield	Sangamon	Illinois
Washington	Daviess	Indiana
Muscatine	Muscatine	Iowa
Machias	Washington	Maine
Hannibal	Marion	Missouri
Missoula	Missoula	Montana
Kearney	Buffalo	Nebraska
Concord	Merrimack	New Hampshire
Pompton	Passaic	New Jersey
Farmington	San Juan	New Mexico
Chapel Hill	Durham	North Carolina
Columbus	Franklin	Ohio
Ponca City	Kay	Oklahoma
Eugene	Lane	Oregon
Chambersburg	Franklin	Pennsylvania
Woonsocket	Providence	Rhode Island
Vermillion	Clay	South Dakota
Sequin	Guadalupe	Texas
Danville	Pittsylvania	Virginia
Seattle	King	Washington
Charleston	Kanawha	West Virginia
Marshfield	Marathon	Wisconsin

and are also shown in the map in Figure II-1. In addition, ten specific sites were identified where it was perceived that the PEF could be part of the solutions to local problems; seven were identified by a state planning agency or energy office, and three by ITC/Solar on the basis of state-supplied information as well as in-house knowledge. These ten sites are listed in Table II-6. They were analyzed according to the screening procedure developed earlier. This analysis is shown in Table II-7.

One of the ten sites, Yazoo City, was identified both by our testing procedure and by responses from the states. None of the other nine sites could compare with those already chosen with the quantitative indexes in the primary screening, but each offered special considerations in the qualitative indexes which made it worthwhile to include the site for further analysis. Bemidji, Minnesota, for example, has a large volume of aspen wood available as a supplemental fuel and a large volume of wastewater for an additional source of water for plantations.

3. Sites Considered For Further Analysis

It was not possible to evaluate all sites with the detailed PEF model because of the extensive effort required to obtain all of the necessary detailed local data. Therefore it was decided to evaluate the six sites identified through the statistical screening procedure and the nine additional sites which had special merit. Statistical data for all sites considered for further analysis are presented in Table II-8. These fifteen sites were evaluated by means of the PEF techno-economic model to illustrate the benefits and costs of PEF at particular sites and to aid the process of selecting the most promising sites which should be considered in the next project phase.

FIGURE II-1

POTENTIAL SITES FOR THE PHOTOSYNTHESIS ENERGY FACTORY

TABLE II-6
ADDITIONAL SPECIFIC SITES

Sites Recommended by States

<u>State</u>	<u>Site</u>	<u>Recommending Agency</u>
Florida	Pensacola	Department of Environmental Regulation Tallahassee, Florida
Michigan	Traverse City	Office of Economic Expansion Michigan Department of Commerce Lansing, Michigan
Minnesota	Bemidji	Minnesota Energy Agency St. Paul, Minnesota
Mississippi	Yazoo City	Mississippi Research and Development Center Jackson, Mississippi
South Carolina	Greenwood	Upper Savannah Council of Governments Greenwood, South Carolina
Tennessee	Knoxville	Tennessee Valley Authority Chattanooga, Tennessee
Texas	Caldwell	Caldwell Chamber of Commerce City of Caldwell Burleson County Industrial Foundation (and other expressions of public support) Caldwell, Texas

Sites Identified by ITC/Solar

<u>State</u>	<u>Site</u>
Kentucky	Maysville
New York	Hammond
Virginia	Martinsville

TABLE II-7
ANALYSIS OF ADDITIONAL SITES

<u>Qualitative Screening</u>								
<u>Site</u>	Participation	Cooling Water	Labor	Demand for Electricity	Demand for Gas	Dry Residues	Wet Residues	Rainfall
Pensacola, FL	+	+	+	+	+	+	+	+
Maysville, KY	+	+	0	+	+	0	+	+
Traverse City, MI	+	+	+	+	+	+	+	+
Bemidji, MN	+	+	+	+	0	+	+	+
Yazoo City, MS	+	+	+	+	+	+	+	+
Hammond, NY	+	+	+	0	0	+	+	+
Greenwood, SC	+	+	+	+	+	+	+	+
Knoxville, TN	+	+	+	+	+	+	+	+
Caldwell, TX	+	+	+	+	+	+	+	+
Martinsville, VA	+	+	0	+	0	+	+	+
<u>Quantitative Screening</u>								
<u>Site</u>	Suitable Acres (1000's Acres)	Land Density ¹	Land Capability ²	Use Value ³				
Pensacola, FL	149.06	0.14	0.95	620				
Maysville, KY	204.06	0.40	0.48	276				
Traverse City, MI	112.01	0.16	0.60	445				
Bemidji, MN	178.13	0.11	0.85	167				
Yazoo City, MS	178.98	0.30	0.64	224				
Hammond, NY	234.56	0.13	0.68	48				
Greenwood, SC	139.94	0.13	0.74	324				
Knoxville, TN	90.35	0.16	0.52	652				
Caldwell, TX	178.13	0.42	0.82	467				
Martinsville, VA	140.22	0.14	0.60	357				

+ , 0 = See Table II-2

¹ Suitable acres divided by total acres at site.

² Weighted average productivity of suitable land at site relative to average cropland, which has a value of 1.00.

³ Weighted average value of suitable land at site.

TABLE II-8
STATISTICAL DATA FOR SITES CONSIDERED FOR FURTHER ANALYSIS

City, State	<u>Kissimmee, FL</u>	<u>Pensacola, FL</u>		<u>Chanute, KS</u>			<u>Maysville, KY</u>		
County	Osceola	Escambia	Santa Rosa	Neosho	Wilson	Woodson	Braken	Fleming	Mason
Urban Population	12,500	59,507			10,600			7,411	
Electricity (\$/kWh)	0.033	0.0289			0.02648			0.026	
Gas (\$/10 ⁶ Btu)	1.15	1.15			0.69			1.11	
Rainfall (inches)	52	64			36			44	
Freeze-Free Days	300+	300			210			180	
Average Size Farm (acres)	2206	170	165	335	461	602	129	139	144
Average Cost Per Acres (\$)	253	602	631	337	304	261	353	353	462
County Size (1000's acres)	840	426	660	335	350	302	131	224	152
Available Acres* (1000's acres)	524	36	113	53	93	76	76	70	57

* Available suitable land in this context means all land in classifications 4, 6, and 7 and land in noncommercial forest and grazed commercial forest in 1, 2, and 3. See reference 6 for further details.

TABLE II-8 (continued)
STATISTICAL DATA FOR SITES CONSIDERED FOR FURTHER ANALYSIS

City, State County	<u>Minden, LA</u>		<u>Natchitoches, LA</u>	<u>Traverse City, MI</u>		<u>Bemidji, MN</u>
	Bossier	Webster	Natchitoches	Grand Traverse	Leelanah	Beltrami
Urban Population	15,300		18,000	18,048		11,490
Electricity (\$/kWh)	0.01935		0.02245	0.027		0.0285
Gas (\$/10 ⁶ Btu)	0.85		0.85	1.43		1.19
Rainfall (inches)	48		56	31		24
Freeze-Free Days	270		240	145		100
Average Size Farm (acres)	285	151	34	137	158	295
Average Cost Per Acres (\$)	527	359	485	741	583	143
County Size (1000's acres)	543	394	827	297	223	1604
Available Acres* (1000's acres)	263	53	414	49	63	178

* Available suitable land in this context means all land in classifications 4, 6, and 7 and land in noncommercial forest and grazed commercial forest in 1, 2, and 3. See reference 6 for further details.

TABLE II-8 (continued)
STATISTICAL DATA FOR SITES CONSIDERED FOR FURTHER ANALYSIS

City, State	<u>Yazoo City, MS</u>	<u>Hammond, NY</u>	<u>Jamestown, NY</u>		<u>Greenwood, SC</u>		
County	Yazoo	St. Lawrence	Cattaraugus	Chatauqua	Abbeville	Greenwood	Laurens
Urban Population	10,796	14,554	39,795		21,069		
Electricity (\$/kWh)	0.0227	0.02822	0.02622		0.02589		
Gas (\$/10 ⁶ Btu)	0.95	2.14	2.14		1.10		
Rainfall (inches)	52	40	36		46		
Freeze-Free Days	250	150	180		240		
Average Size Farm (acres)	520	259	146	207	204	225	235
Average Cost Per Acres (\$)	319	246	474	334	391	381	437
County Size (1000's acres)	600	1771	691	854	324	205	455
Available Acres* (1000's acres)	177	234	50	251	53	43	44

* Available suitable land in this context means all land in classifications 4, 6, and 7 and land in noncommercial forest and grazed commercial forest in 1, 2, and 3. See reference 6 for further details.

TABLE II-8 (continued)
STATISTICAL DATA FOR SITES CONSIDERED FOR FURTHER ANALYSIS

City, State County	<u>Knoxville, TN</u>		<u>Caldwell, TX</u>	<u>Martinsville, VA</u>	
	Knox	Roane	Burleson	Henry	Franklin
Urban Population	174,587		3,558		25,000
Electricity (\$/kWh)	0.0126		0.02104		0.02758
Gas (\$/10 ⁶ Btu)	1.00		1.10		1.78
Rainfall (inches)	48		32		44
Freeze-Free Days	165		270		200
Average Size Farm (acres)	73	111	268	121	156
Average Cost Per Acres (\$)	950	482	467	397	412
County Size (1000's acres)	325	224	1129	252	444
Available Acres *	62	87	179	35	76
(1000's acres)					

* Available suitable land in this context means all land in classifications 4, 6, and 7 and land in noncommercial forest and grazed commercial forest in 1, 2, and 3. See reference 6 for further details.

III. PEF SUBSYSTEMS AND SUBSYSTEM MODELS

A. General

The Photosynthesis Energy Factory (PEF) comprises three major subsystems--the dry-land Energy PlantationTM, a wood-fired power plant, and an algae production system. Various streams of energy and materials flow between these subsystems, as shown in Figure III-1. Wood ash, carbon dioxide, and waste heat flow from the power plant to the algae pond; sludge fertilizer and some reclaimed water flow from the algae pond to the Energy PlantationTM; and wood fuel flows from the Energy PlantationTM to the power plant. To analyze the interactions between the subsystems as the result of these energy and material flows, a comprehensive techno-economic model was developed to describe the performance and the cost of the PEF.

The PEF model incorporates performance and cost models of the three subsystems. These subsystem models were developed with the aid of information and data that have already been developed on the subsystems as the result of previous studies. New data and new concepts have been introduced into the models wherever possible. Previous studies were done on the Energy PlantationTM concept by InterTechnology/Solar Corporation (5,6), and the University of California at Berkeley has been working on algae pond technology for over 20 years.

The model of the wood-fired power plant was developed with basic energy and material balances to represent the operations involved in preparing and using wood chips in a wood-fired boiler to produce steam and ultimately electricity.

These subsystem models are engineering models developed in sufficient detail to represent the important variables and variable-parameter interactions which influence subsystem performance and costs. Of the three subsystem models, the most comprehensive and the most complex is the Energy PlantationTM model, which is a complete design model rather than simply an input-output model.

FIGURE III-1

SCHEMATIC FLOW DIAGRAM OF PHOTOSYNTHESIS ENERGY FACTORY

By and large, the models were developed using available technology as much as possible because one major use of the models is to provide preliminary designs of a demonstration PEF at potential sites. This feature does restrict the use of the models to predict the near-term potential of PEF with improved technology. However, the sensitivity analysis of each model does show what the most influential parameters are, and this information should be useful for guiding related research and development efforts. The models can also be updated and refined easily enough to include technology which will soon be available so that the near-term potential of the PEF can be evaluated in a more definitive manner.

In the following sections, the PEF subsystems and subsystem models are described in detail, including a description of each subsystem and its processes, and a discussion of the development of each model. Calculations with each subsystem model for the best potential sites are presented and analyzed. A sensitivity analysis for each model is presented to point out the most influential parameters affecting performance and cost. Finally, some improvements are suggested for each subsystem and its model, and areas where research can profitably be done to lead to improvements are pointed out.

B. Algae Pond Subsystem

1. General Description of System and Process Alternatives

a. Advantages of the Combined Algae Pond/Energy PlantationTM System

A technical and economic model of an algae pond-based waste treatment system has been developed for use in conjunction with the Photosynthesis Energy Factory (PEF) project. Coupling of the treatment system with the Energy PlantationTM in the PEF simultaneously accomplishes three goals:

- (1) low-cost waste treatment;
- (2) recycling of a portion of the solid, gaseous and thermal wastes of the power plant into algae and, subsequently, SNG production; and
- (3) fertilizer production (through sludge utilization) for the Energy PlantationTM.

The main process elements involved in the algae pond system include: the algae growth ponds, in which carbon, nitrogen and phosphorus are removed from the wastewater and assimilated in algal cell mass; algae harvesting equipment; the digester, which will anaerobically digest primary solids and algal solids; the drying beds, which will dry the algal sludge for use as fertilizer; and the gas cleanup train, which includes carbon dioxide (CO₂) scrubbing, gas drying and pipeline compression. Specific process operations and equipment alternatives will be discussed later.

The environmental benefits of the algae pond system are numerous. The system recycles wastes from the power plant and turns them into useful products. The waste streams from the system are in turn used by the Energy PlantationTM. The wastewater is treated to the required discharge standards. Depending on operational mode, either secondary or tertiary treatment standards can be met. Wastewater treatment sludge, which is a major problem for conventional treatment plants, becomes an environmental credit in the algae pond system in that it replaces conventionally produced fertilizer. Finally, heat from the power plant is utilized, preventing thermal pollution.

The algae pond system also has several advantages in terms of energy conservation and production. At the most basic level, it is a much less energy-intensive form of waste treatment than conventional activated sludge plants. Because of the use of power plant waste heat for digester heating, there is a much higher net yield of digester gas that can be used for its heating value. The energy balance for the algae pond system can be looked at from two perspectives: (1) the actual conversion efficiency from solar insolation to usable fuel, i.e., SNG, or (2) the net energy production based on a gross energy yield of SNG, less the energy required to operate the algae pond system. Table III-1 shows the conversion losses for each step of the fixation and conversion processes. The algae are only able to fix radiant energy in the visible spectrum, which makes up just one-half of incident radiation. The conversion to actual biomass varies with the insolation level; however, an average conversion efficiency of two percent has been assumed for large-scale operations. This will yield approximately ten tons of algal mass per acre per year. The digestion operation yields approximately 5,000 Btu for every pound of algae. After parasitic power requirements are deducted, the overall sunlight-to-fuel conversion efficiency of the algae pond system is on the order of 0.33 percent.

This analysis approach yields important information about which process alternatives can be used to collect solar energy more efficiently. However, it does not fully take into account the advantages of energy conservation, i.e., the use of less energy-intensive methods for waste water treatment and fertilizer production. Table III-2 gives an energy balance for a nitrogen-limited system. In this case, the equivalent energy required to produce an equivalent amount of nitrogen fertilizer and the amount of energy normally required for operating a secondary treatment plant are included with the produced SNG in the determination of the gross energy yield. Energy inputs to the system include: mixing power requirements; compressor and sparger system blower power requirements, and pumping requirements for the microstrainer harvesting system. No

TABLE III-1

SOLAR ENERGY CONVERSION EFFICIENCY OF A NITROGEN-LIMITED ALGAE POND SYSTEM

	BTU / ACRE - YEAR
Incident Solar Radiation*	2×10^{10}
Visible Spectrum	1×10^{10}
Conversion to Biomass ,2% (10 Tons)	2×10^8
Conversion to SNG (1×10^5 SCF)	1×10^8
Process Energy Requirements (11)	3.4×10^7
Net Energy Produced:	6.6×10^7

Overall Sunlight-to-Fuel Conversion Efficiency : 0.33 %

*Representative value equivalent to 340 Langleys/day

TABLE III-2
ENERGY BALANCE FOR 1-MGD NITROGEN-LIMITED SYSTEM*

Basis: 1 year of operation

ENERGY INPUT**

Lift stations and inter-pond pumping, 100 ft head	0.15 x 10 ⁶ KWH
Mixing:	
2 hr/day @ 30 cm/sec	0.10 x 10 ⁶ KWH
22 hr/day @ 5 cm/sec	0.18 x 10 ⁶ KWH
Compressors and sparger system blowers	0.088 x 10 ⁶ KWH
Digester heating - - provided by power plant condenser	0
Microstrainer	
Head loss, 0.5 ft /stage	
Backwash pumps	0.003 x 10 ⁶ KWH
Facility construction, treatment chemicals	??
	<hr/>
	0.52 x 10 ⁶ KWH

ENERGY YIELD

SNG	5.2 x 10 ⁶ SCF	1.5 x 10 ⁶ KWH
Fertilizer, Ammonia equivalent		0.66 x 10 ⁶ KWH
Wastewater Secondary Treatment equivalent		0.22 x 10 ⁶ KWH
		<hr/>
		2.4 x 10 ⁶ KWH
Net Yield = 2.4 x 10 ⁶ - 0.5 x 10 ⁶ = (78% of Gross Yield)		1.9 x 10 ⁶ KWH
		(6.4 x 10 ⁹ Btu)
Net Energy Production Density = 6.4 x 10 ⁹ Btu ÷ 49 acres		1.3 x 10 ⁸ Btu/acre

* Includes energy savings attributable to alternate production of fertilizer and to conventional waste treatment

** Values are for onsite power usage, not primary generation

energy inputs have been assumed for the actual facility construction or production of treatment chemicals for the plant. Using this scheme, the net yield of energy is 78 percent of the gross energy yield. For the system described, the energy production density is 1.3×10^8 Btu/acre-year.

b. General Description of System Unit Operations

i. General

As is the case in all process development work, there are a variety of process options available to accomplish the algae pond system goals. For this study, the process alternatives were restricted to conventional or near-term technology. A list of alternative processes was developed from a literature search and an engineering analysis of parallel processes from the chemical industry.

ii. Sedimentation

Experiments with algae production on sewage have consistently used settled sewage as a substrate. Removal of settleable solids increases light transmission and reduces problem of septicity at the inlet of the algae ponds. Primary sedimentation equipment for the algae pond system is identical to that in a conventional waste treatment plant. The raw wastewater is fed into large, open tanks and the water rises from the bottom of the tank at a rate lower than the settling velocity of the solids. The solids are removed from the bottom of the sedimentation tank and may be processed in a thickener to increase solids content. Thickening is normally justified in conventional wastewater treatment systems because the increased solids concentration reduces the required volume in the digester.

iii. Growth Ponds

Both facultative and aerobic stabilization ponds have been used for

waste treatment in this country for many years. These ponds are from 3 to 15 feet deep. In traditional stabilization ponds, algae photosynthetically produce oxygen which is used by bacterial populations in the pond to reduce BOD_5 (five-day biological oxygen demand) in the sewage. In the deeper ponds, algae settle to the bottom and are anaerobically digested. In this way, the algae do not contribute to suspended solids in the effluent. In contrast, the high-rate oxidation ponds envisioned for the algae pond system are made up of very shallow ponds, on the order of 10 inches deep. In this case, the intent is to maximize production of algal cell mass. Photorespiration and the formation of anaerobic zones in the ponds must be avoided. This necessitates a certain minimum level of mixing and pH control.

The high-rate oxidation ponds are operated as continuously back-mixed biological reactors. They are designed to allow a variable retention time, variable depth, and variable algal density. With the nutrient levels available in sewage, the pond growth system is light-limited. Consequently, yield and retention time will vary with the insolation level. To allow for this variation in retention time, the pond system must be designed to permit hydraulic recycle and control of pond level.

One of the important innovations of the PEF concept is that carbon dioxide from the power plant will be introduced into the high-rate oxidation ponds to allow greater production of algae from the wastewater stream. Carbon is normally the limiting nutrient in municipal wastewaters. Nitrogen is normally the next nutrient to limit growth. To reach the phosphorus growth potential, it will be necessary both to add carbon dioxide and to maintain nitrogen-fixing species of algae in the pond. Application of carbon dioxide to the pond cells will also have the added benefits of sparging photosynthesis oxygen and reducing the pH. Without this carbon dioxide transfer, the pH would rise as bicarbonate is removed from the pond waters. In the algae pond as it is usually operated, the pH is not controlled, and the pH does rise, resulting in a decline in the algae growth rate.

Various methods for transferring flue gas carbon dioxide to the pond waters have been proposed. Two methods may be drawn from conventional wastewater treatment practice: (1) mechanical surface aerators and (2) diffused-aeration spargers. Other possibilities include scrubbers using pond water, venturi mixing tubes, and airlift pumps. Without further developmental work, the only two systems which could be applied immediately are the surface aeration and sparging systems.

iv. Harvesting

Unlike algal growth in conventional stabilization ponds, the algae in high-rate ponds are harvested for subsequent digestion to SNG. Reliable low-cost harvesting has been a major problem in mass algal culture. A variety of methods has been presented in the literature (13, 14, 15, 16, 17). They include: sedimentation with and without chemical coagulation; dissolved air flotation (DAF); sand or multimedia filtration; microstraining; ultra-filtration; centrifugation; and ion exchange. Recent stabilization pond projects which have received Environmental Protection Agency (EPA) construction grants have relied most heavily on coagulation/sedimentation and/or intermittent sand filtration for suspended solids removal. These methods are low in cost, but they produce a sludge which may not be acceptable for digestion. On the other hand, ultra-filtration, centrifugation, and ion exchange systems produce a high solids-content, relatively pure algal sludge for digestion. Unfortunately, they have high capital and operational costs. Research at the University of California at Berkeley (UCB) indicates that microstraining may be an effective compromise. It is low in cost and reasonably effective on larger algal species. Microstraining has been used effectively in conventional waste treatment polishing systems (12, 18).

v. Anaerobic Digestion

While there is very little pilot-scale data concerning anaerobic digestion of algae, lab-scale work indicates that algal cells behave much like

conventional waste treatment solids. Gas yields appear to be similar to conventional systems. As is true in conventional digestion, temperature is an important parameter in gas yield. Based on data from UCB, operation in a mesophilic range (up to 110°F) appears to be most cost-effective. At 95°F, a retention time of over 11 days is required to prevent washout of methane-forming bacteria (19). Increases in retention time beyond this point will yield increased gas production, which must be balanced against the increased capital cost of the larger digester.

vi. Sludge Dewatering

To reduce the cost of transportation to the Energy PlantationTM, settleable solids from the digester must first be dewatered. Fly ash from the PEF power plant can be used to facilitate the dewatering operation. In this way the PEF can recycle nonvolatized nutrients from the wood and alleviate a separate ash disposal problem.

There are currently three proven processes for sludge dewatering--belt filters, centrifuges, and drying beds. Belt filters dewater sludge by pressing the sludge between two porous belts, forcing the water through the belt. Centrifuges dewater sludge by increasing the g forces on the sludge to the point where the solids will settle more quickly. Drying beds are simply sand beds on which the sludge is spread. Unlike the other two methods, the separation mechanism in the sand beds is draining as opposed to settling. Belt filters and centrifuges are capital-intensive. By contrast, if low-cost land is available, sand beds are relatively inexpensive to construct but involve high operating costs for removal of solids and replacement of sand.

vii. Gas Processing

The raw gas coming off of the digester is approximately 65 percent methane

and 30 percent carbon dioxide. It is saturated with water. There may also be traces of hydrogen sulfide and other acid gases. If the intention is to produce a fuel gas of pipeline quality, the digester gas must go through a cleanup system. The first major operation is removal of the carbon dioxide. Numerous processes include high-pressure scrubbing with water and scrubbing with one of a variety of alkaline solutions (20, 21). Two processes using alkaline scrubbing agents are the Vetricoke and the Benfield systems (22). The primary advantage of these systems over a simple water system is that they have significantly higher capacities for carbon dioxide because of the chemical reaction which takes place. Another hybrid system that has been suggested would use pond water as the scrubbing agent. The ponds have slightly elevated pH. This fact will enhance the capacity for carbon dioxide absorption. However, the pond water will also contain algal cells, which will introduce biofouling in the system.

Gas coming from any of the carbon dioxide scrubbing systems will contain a maximum of one percent carbon dioxide and will be saturated with water vapor at the exit temperature of the scrubber. To prevent formation of corrosive acids in the pipeline, it is necessary to dry this SNG to approximately seven pounds of water for every million cubic feet. Two methods for gas drying are used commercially. In the natural gas industry, the most widely used method involves an absorption tower using ethylene glycol as the dehydrating agent (23). The glycol solution is regenerated in a separate stripping tower. Smaller scale gas-drying operations may use packed beds of silica gel for absorbing the water from the gas stream. Absorption will result in much lower residual water vapor levels than the glycol scrubbing system but at a much higher capital cost.

2. Description of Performance Model

a. General Considerations

A computer model has been developed to predict the performance of the algae pond system using a variety of process options. The model is subject to the following guidelines and constraints:

- (1) The volume and chemical nature of the wastewater flow are required as input data;
- (2) The quantities of flue gas and waste heat available from the power plant must be supplied as input;
- (3) Algae production is determined by the potential of the waste stream, not by the amount of flue gas carbon dioxide (CO_2) available.

The performance model reflects and is limited by the current state-of-the-art in algae growth. Mass culture of algae is a rapidly developing area; however, several important, basic relationships have yet to be quantified. As a result, several parameters which eventually will be the output of the technical design must be introduced as input data. For example, the level of wastewater treatment is only partially predictable by the process options selected. Nutrient removal efficiencies must be inputted for each different level of treatment. Similarly, the solar conversion efficiency cannot be predicted by the model and must be inputted. Conversion efficiency is, in actuality, a function of operational procedures--mixing rates, algal densities, pond depth, and the chemical parameters of the pond. Finally, as was previously mentioned, algae digestion is essentially a "black box" operation at this point. This fact prevents a quantitative assessment of nitrogen and phosphorus mass balances in the system.

Within these limitations, equations have been developed to predict: (1) the flows and (2) the required equipment sizes for the various process

operations. The specific equations appear in Appendix B. A list of the included equipment for each of these operations appears in a separate section of Appendix B, which deals with cost parameters. The subsections of the report which follow will deal with the selection and justification of the technical design approach used for each of the process operations and will present the default values of design parameters.

b. Sedimentation/Thickening

Three design methods--each based on a different operational parameter--are currently used for the design of conventional primary sedimentation facilities. These parameters include weir-loading rate, tank overflow rate, and sedimentation detention time. The overflow rate is established experimentally and is equivalent to an upflow velocity lower than the settling velocity of suspended solids in the raw wastewater stream. Since it has as its basis the physical phenomenon which takes place in sedimentation, overflow rate is most widely used in design of sedimentation facilities. The default design values which will be used in the model are (12):

- (1) Fifty percent suspended solids removal;
- (2) Sedimentation tank overflow rate of 800 gallons per day per square foot;
- (3) Thickener design loading rate of 20 pounds per square foot per day;
- (4) BOD₅ removal efficiency of 34 percent; based on EPA data;
- (5) Phosphorus removal efficiency of 9 percent based on EPA data; and
- (6) A thickener solids concentration of twice that coming from the sedimentation tank.

Some organic nitrogen is also removed in primary sedimentation, but the amount varies widely. The University of California at Berkeley data

indicate that approximately 15 percent of total nitrogen may be removed in primary sedimentation.

c. Algae Pond Carbon Balance

The ultimate amount of algae that can be produced from a given wastewater stream is a function of the nutrient makeup of that stream and the available nutrient resources. To determine the maximum annual algae production, it is necessary to develop nutrient balances around the entire algae pond system. Of the three major nutrients in municipal wastewater--carbon, nitrogen and phosphorus--carbon is normally the first to be exhausted and consequently to limit growth. Nitrogen is normally next to limit biomass production. A carbon balance around the algae pond system can be made to determine the amount of flue gas carbon dioxide (CO_2) required to attain the higher theoretical production of the nitrogen or phosphorus limit. Figure III-2 shows the various influent and effluent streams and the important carbon sources in the system.

The computer model of the carbon balance first calculates the theoretical production of algae based on the amounts of nitrogen and phosphorus that are to be removed from the wastewater. Estimates of maximum potential algae production for each nutrient are based on growth potentials which correspond to the ratio of total unit algal cell mass to the weight of either nutrient in a unit cell mass. The model selects the nutrient with the lesser theoretical production as the limiting nutrient. If, however, the ponds are to be operated utilizing the blue-green algae or other nitrogen fixers, essentially an infinite supply of nitrogen exists and phosphorus becomes the limiting nutrient. Potassium or trace minerals could also limit growth, but these nutrients are abundantly present in municipal wastewaters. They are not of major significance as water pollutants. They have not, consequently, been considered.

The model next determines the theoretical algae production based on carbon in the municipal effluent that is available for algae growth.

FIGURE III -2
ALGAE POND SYSTEM CARBON BALANCE
 Major Carbon Sources/Losses in System

Again, a growth-potential multiplier is used to determine biomass. There are several analytical procedures to identify carbon in the effluent. These include total organic carbon (TOC), chemical oxygen demand (COD), five-day biological oxygen demand (BOD_5), and carbonate and bicarbonate alkalinity. The usefulness of each test in predicting the potential for algal biomass production varies with the species used and the type of pond. The alkalinity test, for example, measures the presence of inorganic carbon in the wastewater. This number would be valuable if monocultures of algal autotrophs (species using the inorganic carbon sources) were being used. In reality, municipal and industrial effluents provide a ready supply of organic carbon; this situation favors populations of photomixotropic species which utilize inorganic and organic substrates. Assuming flue gas CO_2 is available to recarbonate and neutralize the effluent, there may be a very small net utilization of carbonate alkalinity. Consequently, alkalinity is not considered in the growth modeling.

Of the other three tests, BOD_5 appears most suitable for predicting algal growth potential. BOD_5 tests measure the readily oxidizable material in the waste stream. Extensive experience with the tests indicates that nitrogenous oxygen demand is not significantly exerted until about after seven days. Consequently, the BOD_5 tests measure the readily oxidizable carbonaceous material. A growth-potential multiplier of 0.7 mg algae per mg of BOD_5 was calculated by assuming the BOD_5 is nearly pure carbon. The derived multiplier agrees well with empirical data on BOD_5 utilization from UCB.

Assuming carbon is limiting, the model must calculate the amount of CO_2 required to maximize algae production. This is a two-step procedure. First, the CO_2 required to produce the previously calculated growth potential of either nitrogen or phosphorus is calculated. This value is compared with the CO_2 available. If insufficient CO_2 is available, the procedure is redone to calculate the algae which can be produced using the available CO_2 .

The output of the model is the amount of algae that can be produced at a selected treatment level and the amount of CO_2 that must be added to attain the required nutrient removal by algae cell production.

d. Yield Calculations

The average annual per-acre yield of algae is based on a solar conversion efficiency. In this model the conversion efficiency is an input parameter. The calculation of annual yield is preceded by a screening of monthly average ambient temperatures at a given site to determine the number of months the system can be operated annually. With proper selection of algal species, temperature does not influence growth rate until the average temperature drops to below around 5°C , or 40°F (24). Below this temperature, the growth rate declines rapidly and the required nutrient removal efficiencies cannot be met. During these months, the wastewater must be stored for subsequent treatment. Algae may be grown on this stored wastewater during the following summer, but this potential biomass production has not been included in the yield model due to the unpredictable losses in nutrients in the stored wastewater.

The design requirement for calculation of per-acre yield involves meeting necessary wastewater treatment standards in the worst-case month. The operating month with the lowest average daily insolation is selected as the design case. Because photosynthetic processes become saturated at relatively low light intensities, this month will have the highest value of conversion efficiency, assumed for this system to be four percent. The resultant yield, when multiplied by the number of operating months, will give an equivalent annual yield. Insolation at a given site may go up by a factor of three between winter and summer. However, conversion efficiency may drop by a factor of two at the higher insolation levels. The net effect will be a reduction in required pond area in the summer. Although more algae could be produced if the

seasonally inactive pond cells could be utilized, the average annual yield for all acreage is limited to the product of the design monthly yield times the number of operating months.

Figure III-3 shows values of predicted monthly (for the design worst-case month) and annual yields for locations throughout the United States. The monthly yield for the worst-case month used for design for a particular site is a function of the average daily insolation during that month. Because the pond will be operated for a different number of months in different locations, a different month is used for the design worst case in different locations, and this procedure can make a comparison of design monthly yields in two locations misleading.

For example, the design monthly yield for a northern location can be higher than that for a more southerly location because for the former case, the average daily insolation in the worst-case month can be higher since the worst-case month may be later in the spring or earlier in the fall. The amount of cloud cover at a particular location also influences the average daily insolation. Thus, in comparing the monthly yields for Wisconsin and Illinois, for example, it should be realized that the operating season is only 7 months in Wisconsin, but 8 months in Illinois. The average daily insolation for the design case in Illinois is lower than that for Wisconsin. Similar considerations apply in other comparisons of monthly yields in different locations.

FIGURE III - 3

ALGAL YIELDS FOR REPRESENTATIVE LOCATIONS ACROSS THE U.S.*

Upper Number: Lowest Potential Monthly Yield During Operating Season, Tons of Dry Algae Per Acre-Month

Lower Number: Resultant Annual Yield, Tons of Dry Algae Per Acre-Year

*Climatological Data from "Low Temperature Engineering Application of Solar Energy", by American Society of Heating, Refrigerating, and Air Conditioning Engineers.

e. Harvest Cycles

After the total pond surface area is determined, it is necessary to determine how many pond stages must be operated in series to obtain the optimum algal yield. Municipal wastewaters may have a phosphorus-limited growth potential of 1500 mg/l of algae. Not only would high algal concentrations prevent photosynthesis in the lower level of the pond due to light absorption, but they would encourage settling of the algal cells and subsequent loss of biomass through fermentation. For this model the design algal concentration has been taken as 200 mg/l. If this number were to be raised, the number of harvest stages would decrease, but light penetration would decrease. Lowering the algal concentration would increase photosynthetic efficiency, but would result in more pond stages and harvesting equipment to reach the same growth potential. The optimum algal density in the pond cells is a tradeoff between algal yield and the capital cost of the harvesting system.

The pond system may be envisioned as a number of pond cells operated in series. Conceptually, each stage is a stirred, back-mixed biological reactor. Each stage must have sufficient area to produce algae equivalent to an increase in algal concentration in the influent up to the optimal algal density. The model calculates the amount of area required to produce this increase of algal concentration for each stage. It repeats this procedure until the total amount of algae produced is equal to the algal growth potential for the wastewater stream.

f. Dissolved Air Flotation (DAF) Harvesting

Dissolved air flotation was selected as a candidate method for algae harvesting for a variety of reasons. The system has the demonstrated ability to remove algae and produce a solids concentration in the resultant sludge of between three percent and four percent (25). This harvesting method also offers the opportunity for mass transfer of carbon dioxide in the sparging gas. The basic limitations of dissolved air flotation are that it is comparatively capital-intensive and it requires chemical conditioning of the influent stream. Chemical dosage is roughly equal to

the algal concentration, and consequently, a large quantity of chemicals would be sent to the digestion step. The default design values for the DAF subroutine model are listed below (25):

- (1) a surface-loading rate of 2 gallons per minute per square foot based on influent flow without recycle;
- (2) 0.012 cubic feet per minute of insoluble gas per gallon per minute flow; and
- (3) an alum dosage of 175 mg/l.

g. Microstrainer Harvesting

Microstraining is still being developed as an algae harvesting system. It is most effective on large species of algae. A microstrainer is a revolving drum coated with a fine mesh screen which strains solids from the influent stream. Solids are released from the screen through the use of continuous backwash sprays. The maximum solids concentration obtainable in the resultant sludge is limited because of the continuous backwash. A tenfold increase in concentration over the influent is a good average. Consequently, two microstrainer stages are required at each harvesting stage. The second stage however requires only one-tenth the flow capacity of the harvesting unit. Sizing of microstrainer equipment is based on the required submerged surface area on the drum per unit flow. The design value for this model will be a hydraulic loading of five gallons per minute per square foot of submerged drum (12). This loading rate has been used successfully in experiments at the University of California at Berkeley.

h. Algae Digestion

Two design methods are available and currently being used for sizing conventional digesters in waste treatment facilities. Digester tanks can be sized based on a design volatile-solids loading or on a solids retention time. Retention time is established by determining the growth rate of methane-producing bacteria. The design retention time will be a period longer than the critical retention time at which the

methane-producing bacteria cannot maintain a stable population size. Because of its relation to the biological phenomena which occur in digestion, retention time is the most suitable design parameter and has been selected for use in this model.

A related and very important design parameter in digester operation is operating temperature. Experimental work indicates higher gas yields at higher digester temperatures (19). Bench-scale experiments at the University of California at Berkeley suggest that the reason for the higher gas yield is that the high temperatures destroy the algal cells, making them more susceptible to digestion than viable cells. The increase in gas yield must be traded off against the increased cost of insulation and heat exchange equipment. The most cost-effective operating temperature appears to be around 95°F. Waste heat from the power plant condenser is available to supply this low-level demand. At this temperature, gas production is approximately five cubic feet of methane per pound of algal volatile solid introduced to the digester.

i. Digester Sludge Dewatering

Digestion of primary solids and algae results in a 50-percent reduction in settleable solids. Dewatering of this digested sludge is necessary to minimize transportation costs in delivering the sludge to the Energy PlantationTM. Work with algae dewatering at the University of California at Berkeley indicates that sand drying beds are suitable for this purpose. Underflow from the sand beds is recycled to the algae ponds. Fly ash from the power plant can be used as a dewatering aid on the sand beds and will add nutrients to the sludge going to the Energy PlantationTM.

Sand bed cost is primarily a function of required surface area (26). The required surface area is calculated based on a design solids loading. EPA data indicate that a value of 18 pounds per day per square foot of sand bed will be necessary.

j. Gas Scrubbing, Drying, and Compression

To produce pipeline-quality SNG, it is necessary to remove the CO_2 from the digester gas. Three basic types of processes have been developed for industrial CO_2 removal. They include absorption in pure water, in amine solutions, and in carbonate solutions. All systems consist of at least two towers. In the first tower, the gas is contacted with the absorbing liquid and mass transfer of CO_2 occurs. In the second tower, the absorbing liquid is stripped of CO_2 or otherwise regenerated prior to its return to the absorbing column.

All of the commercial systems use some method to enhance the capacity of the absorbing liquid for CO_2 . In the case of the water system, the absorption tower is operated at very high pressure, which increase the partial pressure of carbon dioxide and, consequently, increases its solubility in the water. In the case of the amine and carbonate systems, a chemical reaction occurs which allows more CO_2 to be transferred to the absorbing solution. The least costly of the chemical absorption systems is the Benfield hot potassium carbonate system. While the details of the operation are proprietary, the system uses both pressurization of the gas stream and chemical reaction to increase the rate of, and capacity for, absorption.

The SNG coming from the Benfield unit will then go to a glycol dryer. The dryer system is likewise made up of two towers, an absorber and a regenerator. The drying system dries the gas to approximately seven pounds of water vapor per every million cubic feet of SNG. When the gas leaves the dryer, it is compressed to 1000 psia for pipeline transmission. At this point the gas stream is approximately 93 percent methane and less than one percent carbon dioxide. The remainder is hydrogen and short-chain hydrocarbons. Sizing and cost estimation of the scrubbing, drying and compression units are based on the gas flow to each of the systems.

k. Sparging System

The recarbonation system for the algae ponds is modeled after a diffused air system in a conventional activated sludge plant. The system design is based on the required gas flow. In the hybrid system developed for the PEF, header pipes are placed along the bottom of the ponds at the mixing station. At regular intervals along the pipes are valved orifices. The main headers will be located between rows of pond cells. Pond mixing equipment will be situated at the end of the pond cell nearest to the sparger header. Experimental data are available for mass-transfer correlations under the pond conditions. Engineering calculations indicate that the transfer efficiency in the shallow oxidation ponds will be on the order of 15 percent.

3. Description of Cost Model

a. Equipment Cost

A cost model of the algae pond system has been developed to allow evaluation of the life-cycle cost of various processing schemes. Equations for installed capital costs and operating and maintenance (O and M) costs have been developed for each piece of equipment. A specific listing of the data resources for these cost equations appears in Appendix B. Also included in this Appendix is a table which contains the specific cost items included in the cost equations. Where possible, data for the actual piece of equipment to be used were located and used for cost equations. However, in situations where there is no present equivalent to the process, parallel processes from current technology were assessed.

In formulating the cost equations, the prevailing values for land cost, pipeline gas cost, labor rates, and power costs for the specific candidate site were used. The wastewater treatment credit was taken from a national survey of the capital costs of wastewater treatment plant construction done

by EPA (27). This study found that the amortized capital cost of construction of secondary plants was approximately 52¢ per thousand gallons treated. A separate study for the EPA done by Bechtel estimated the operation and maintenance costs for a secondary treatment plant at approximately 36¢ per thousand gallons treated, yielding a total cost of approximately 88¢ per thousand gallons (28). A scale-up factor of 1.52 was used for escalating costs for tertiary treatment (26).

It was not possible to predict a site-specific wastewater treatment credit because of the many site-specific variables included. These include: location of the wastewater treatment plant; required collection and pumping system for wastewater; and specific plant modifications necessary for local industrial wastes.

b. Cost Equations

Where cost equations were not already available, data were fitted to a power curve of the form:

$$C = C_0 (X/X_0)^b \quad (\text{III-1})$$

where

C_0 = the baseline cost for a specified reference system

X_0 = the value of the relevant equipment cost parameter for the reference system (this maybe surface area of the tank, screen area, pond surface, etc.)

X = the value of the equipment cost parameter for the specific system being evaluated

b = cost exponent

The values for C_0 , X_0 , and b for each piece of equipment are found in Appendix B, along with a description of the reference system.

It is difficult to estimate the accuracy of the cost equations because the data from which they were developed were not for the specific application

intended in this model. Accuracy of curve-fitting procedures is estimated at ± 20 percent in the worst case. The validity of the cost equations for equipment-costing extends over the range from roughly one million gallons per day to 100 MGD. However, pond installations of more than 1,000 acres probably could not be costed with the available equations. It is improbable that 1,000 acres of level land could be found in the PEF site, and consequently, much higher significant excavation costs would be incurred. Algae pond systems for sites larger than 1,000 acres would have to be costed on a site-by-site basis.

c. Financing Procedures

Two methods have been used for evaluating the life-cycle cost of the various algae pond systems. The utility method involves mixed financing for obtaining necessary capital. A portion of the annual income is in this case taxable under IRS statutes. An average discount rate was developed for the utility financing method. In this model a value of 11.1 percent was derived.

Alternatively, a municipal financing method may be used. In this case, the municipality finances the project through low-cost municipal bonds. No tax obligation is incurred. The discount rate is equal to the interest rate on the bonds. In this case 6.375 percent per annum will be assumed. This is the discount rate set by the Water Resources Council for estimating water resources projects in fiscal 1977. The municipal financing procedure has been chosen for use in the overall analyses of the algae pond system. This selection was made primarily because this method reflects current practice in treatment systems dealing with municipal domestic wastes. A complete description of the utility and municipal financing methods appears in Appendix A.

d. Applications of Cost Model

The output of both the utility and municipal financing methods is an equivalent annual expense for the given algae pond system. This number can be combined with the cost credits in a variety of ways depending on

the desired analysis. In industrial cost analysis, the expenses and credits would be combined and an iteration performed to determine the rate of return for the case when the net annual cash flow is equal to zero. However, in the case of the algae pond model that has been developed, the discount rate has been set as an input variable. Consequently, the net annual cash flow must be allowed to fluctuate. In the actual analysis of a wastewater treatment system, this net annual cash flow would be applied to reducing the sewer charges for the occupants of the municipality. This would yield a zero net annual cash flow by reducing the waste treatment credit. However, such rate scheduling is beyond the scope of this project. Using the prevailing local values for gas cost, then, the gas credit and gas treatment credit may be subtracted from the equivalent annual expense, resulting in a net annual cash flow. This value may be used to compare the life-cycle cost and cost-effectiveness of algae pond system process alternatives or for comparing algae pond systems at specific sites. In the analysis of the PEF as a whole, the positive cash flow will be used to reduce the price of the generated electricity.

Another important use of the life-cycle cost information is for determining the equivalent price of gas produced by the algae pond system. This is done by comparing the gas yields, annual expenses, and credits for the carbon-limited growth case with either the nitrogen- or phosphorus-limited growth case. An equivalent gas cost can be calculated by dividing the change in the difference between annual expenses and wastewater treatment credits for each system by the change in gas production between the two systems. This number will determine whether or not a system should be built, for example, to the phosphorus limit.

A third related use of the life-cycle cost data is to determine areas for cost-reduction research priority. Each piece of processing equipment can be evaluated in terms of its impact on the equivalent annual expense. In this manner it is possible to compare the effect of capital costs, O and M costs, interest on working capital and land, and interest during construction for their relative effect on cost-effectiveness of the system.

4. Description of Optimized System

a. Sensitivity Analysis

The combined technical performance and cost model of the algae pond system was used to evaluate a variety of process options, processing sequences, and operating parameters. The base case system was a hypothetical 1-MGD secondary treatment plant in Greensboro, North Carolina. A summary of the effect of the various process alternatives on net annual cash flow and capital investment appears in Table III-3. The table also includes a brief comment on the effect of the alternative on the design and the tradeoff involved in the process alternative. From the table, two major influences on the cost-effectiveness of the algae pond system are apparent. They are:

- (1) months of operation per year; and
- (2) the level of waste treatment.

The major impact of not being able to operate twelve months out of the year is that a duplicate wastewater treatment system must be built to handle wintertime wastewater flows. This may be simply large holding ponds to store the flow during nonoperational periods or it may be an actual parallel treatment system. The model assumes that the wastewater treatment credit must be decreased proportionally to the decrease in operating time during the year. While it is conceivable that the wastewater stored during the winter could be used for algae production during high-insolation summer months, it is not possible to quantify the loss of nutrients that would take place in the holding pond during storage. As a result, no credit can be taken for this possibility.

Table III-4 gives in more detail the effect of wastewater treatment level on the cost-effectiveness of the algae pond system. Cash flow decreases as the level of treatment increases. For the case of nitrogen-limited growth, no additional wastewater treatment credit has been taken above the

TABLE III-3

TECHNICAL AND ECONOMIC EFFECTS OF PROCESS ALTERNATIVES*

<u>Alternative</u>	<u>Net Annual Cash Flow (Municipal Financing)</u>	<u>Capital Investment</u>	<u>Effect on Design</u>
(Base Case)	\$213,000	\$790,000	-----
I. Local Customer for untreated digester gas	\$222,000	\$727,000	Because of the low transfer efficiency of sparging in the ponds, the savings in the Benfield system, compressors, and dryer costs only slightly exceed the added cost of applying extra flue gas. The analysis assumes the same price per million Btu as pipeline gas.
II. Crop irrigation with digested sludge	\$226,000	\$739,000	No sand bed is required. No costs have been included for transportation and application.
III. Decreased algal concentration (150 mg/l)	\$202,000	\$870,000	Low concentration will necessitate additional harvesting stage. Conversely, higher concentration will reduce the number of stages. The model does not predict the effect of changes in algal density on pond yield.
IV. Thickener or primary sedimentation	\$206,000	\$838,000	The thickener only reduces the digester volume by 15% because of the digester influent comes from the algae harvester. This does not offset the cost of the equipment.
V. No concrete erosion protection in pond construction	\$221,000	\$715,000	Pond construction costs are reduced from \$13,200 to \$10,200 per acre for 25 acres
VI. Change in minimum allowable growth temperature (to 50°F)	\$138,000	\$732,000	Inability to operate 12 months every year necessitates additional storage and treatment capacity.

*Base Case: 1-MGD Carbon-limited Algae Growth Facility designed to Greensboro, N.C. Climatological Data

TABLE III-3

(continued)

VII. Control of operation allowing 6% visible solar energy conversion in winter months	\$223,000	\$709,000	Reduces required pond area.
VIII. Increased gas yield digester (6 SCF/pound of volatile, introduced)	\$214,000	\$793,000	At constant digester size, the increased gas production credit is approximately offset by the increased gas handling costs.
IX. Addition of flue gas CO ₂ to increase production to nitrogen limited growth potential	\$152,000	\$1,241,000	Increased gas yield does not presently justify the additional cost of ponds, CO ₂ transfer, etc.
X. Use of flue gas CO ₂ and nitrogen-fixing blue green algae to increase production to phosphorus-limited growth potential	\$58,000	\$3,294,000	A fourfold increase in capital costs outweighs the 50% increase in waste treatment credit due to tertiary treatment.
XI. Dissolved air flotation harvesting in Case X	-\$171,000	\$3,873,000	The actual reduction of sparger air flow (Case X) is small (2%). The higher sludge concentration attainable reduces the digester volume by 27%. This does not offset the high capital and operating (chemicals) costs.
XII. CO ₂ transfer efficiency of 50% in Case X	\$92,000	\$3,086,000	Lower capital and operating costs due to 70% reduction in required flue gas flow.

TABLE III-4

TECHNICAL AND ECONOMIC EFFECTS OF WASTEWATER TREATMENT ALTERNATIVES

Parameters for 1-MGD Base System	Limiting Nutrient		
	<u>Carbon</u>	<u>Nitrogen</u>	<u>Phosphorus</u>
Pond Area, Acres	25	48	193
Methane Production SCF/Year	3.18×10^6	5.16×10^6	17.6×10^6
Fertilizer Equivalent			
Tons N/Year	32.8	43.8	176.5
Tons P/Year	4.1	7.2	19.5
Capital Cost	\$790,000	\$1,241,000	\$3,294,000
Treatment Credit	Secondary	Secondary	Tertiary
Net Annual Cash Flow	\$213,000	\$152,000	\$58,000
Incremental Cost of Gas* \$/1000 SCF	-----	\$32.83	\$12.78

*Incremental cost is the ratio of the change in the difference between treatment credit and equivalent annual expense to the change in annual gas production, i.e.

$$\text{Cost} = \frac{\Delta(\text{treatment credit} - \text{annual expense})}{\Delta 1000 \text{ SCF Units}}$$

based on a comparison with the carbon-limited case.

secondary treatment credit. This is because tertiary treatment deals primarily with phosphorus removal. Consequently, expanding the plant to the nitrogen-growth limit is not cost-effective, which is reflected in the high incremental cost of gas (\$32.83/1,000 SCF).

Tertiary treatment using blue-green algae to fix nitrogen is not possible with near-term technology. However, when species control does become available, phosphorus-limited growth systems may be cost-effective. The incremental cost of gas when compared with the carbon-limited base case system is \$12.78/1000 SCF. This value represents the average cost of gas over the 20-year lifetime of the project. Assuming a 10 percent annual escalation of gas price, it is equal to a present cost of approximately \$5 per thousand standard cubic feet. To produce gas with an equivalent present cost of \$2/1000 SCF, the equivalent annual expense of the phosphorus-limited system must be reduced approximately 25 percent.

Figure III-4 shows the effect of plant size on net annual cash flow. The curve is a hybrid of the curves for wastewater stabilization ponds and conventional secondary treatment plants. Normally, stabilization plants would be most cost-effective at the low design flows. However, the algae pond system incorporates much of the hardware of a conventional plant, i.e. digesters, sludge, handling facilities, etc. These units are most cost-effective for larger design flows. Consequently, the system is not cost-effective for very small flows. At larger flows, economies of scale associated with conventional sewage treatment plants become apparent. The curve does not include the nonquantifiable effect of finding sufficient level land for very large installations. It is assumed that the curve would peak out and then bend down as additional excavation costs drove pond construction cost up at larger plant sizes.

b. Base Case System

The foregoing discussion indicates that the carbon-limited growth case is at present the most cost-effective system. This system meets secondary treatment standards. Assuming advances in development of (1) low-cost process alternatives and (2) species control for blue-green algae, expansion

FIGURE III-4

EFFECT OF ALGAE FACILITY SIZE ON ECONOMICS

Design Basis: Carbon-Limited System, Greensboro, N.C.

to the phosphorus-limited growth case may be cost-effective in the near future. A computer listing of the summary of technical and economic design data on the optimized base case appears in Tables III-5 through III-7. The 1-MGD carbon-limited system is based on climatological data for Greensboro, North Carolina. The system is based on conventional equipment and is designed to be universally applicable; i.e., it provides pipeline-quality gas and dried sludge for use as fertilizer. The system operates twelve months out of the year. Optimization indicates that no thickener is necessary. Also, all harvesting is done using microstrainers. Using municipal financing, the base case has a positive net annual cash flow of \$213,000 per year.

5. System Performance at Potential Sites

The algae pond system developed for the base case was applied to each of 15 candidate PEF sites using local data on net evaporation (pan evaporation-precipitation) rate, monthly average insolation and temperature, wastewater flow, and costs. Local costs include the cost of pipeline gas, the cost of labor for operating the plants, and the cost of utilities. The wastewater treatment credit used was a national average for secondary treatment costs. A computer run was made for each site for the carbon-limited case, the nitrogen-limited case, and the phosphorus-limited case. The results of these computer runs are summarized in Tables III-8 through III-10. Tables include data on total pond area, SNG production, capital investment and net annual cash flow. In addition, a normalized net annual cash flow, based on a 1-MGD system at the specific site, was developed for the carbon-limited growth case. This normalized cash flow allows direct comparison of the operating capabilities of the various systems. The major factors which influenced the relative value of the cash flow at the different sites were months of operation, the level of treatment, and the plant size.

Higher levels of treatment result in lower net annual cash flows and increasing capital cost. Compared to the carbon-limited case, the

TABLE III-5
ALGAE PRODUCTION SYSTEM

PROCESS -----	EQUIPMENT SIZING -----	COSTS, IN FALL 1976 DOLLARS -----	
		CAPITAL -----	ANNUAL O AND M -----
SEDIMENTATION	TANK SURFACE AREA: 1250. SQ FT	\$ 79500.	\$ 5370.
	THICKENER SURFACE AREA: 0. SQ FT	\$ 0.	\$ 0.
ALGAE PONDS	POND SURFACE AREA: 25. ACRES	\$ 330229.	\$ 5920.
HARVESTING (FLOTATION)	NUMBER OF HARVEST UNITS: 0		
	TOTAL SURFACE AREA: 0. SQ FT	\$ 0.	\$ 0.
(MICROSCREEN)	NUMBER OF HARVEST UNITS: 1		
	TOTAL SCREEN AREA: 139. SQ FT	\$ 77507.	\$ 3354.
DIGESTION	TANK VOLUME: 20894. CU FT	\$ 222638.	\$ 10593.
CO2 ABSORPTION	COMPRESSOR HORSEPOWER: 3.	\$ 16932.	\$ 1553.
CO2 TRANSFER	SPARGER GAS FLOW: 3. SCFM	\$ 4022.	\$ 289.
GAS TREATMENT	COMPRESSOR HORSEPOWER: 1.	\$ 7672.	\$ 326.
SLUDGE DRYING	SAND BED SURFACE AREA: 0.5 ACRES	\$ 51082.	\$ 7174.
		-----	-----
TOTAL DEPRECIABLE INVESTMENT:		\$ 789583.	
TOTAL ANNUAL O AND M EXPENSES:			\$ 34579.
TOTAL SITE REQUIREMENTS: 36. ACRES			
NONDEPRECIABLE INVESTMENT FOR LAND:		\$ 17900.	

TABLE III-6
ALGAE PRODUCTION SYSTEM

SUMMARY OF TECHNICAL AND ECONOMIC ANALYSES

POHD SYSTEM DESIGN:

DESIGN WASTEWATER INFLUENT FLOW: 1.88 MILLION GALLONS PER DAY (MGD)

DESIGN EFFLUENT FLOW: 1.88 MILLION GALLONS PER DAY

EFFLUENT CONCENTRATIONS:

SUSPENDED SOLIDS: 28. MG / LITER

BOD₅: 38. MG / LITER

NITROGEN: 16. MG / LITER

PHOSPHORUS: 12.8 MG / LITER

TOTAL ACREAGE REQUIRED FOR PONDS, BUILDINGS, TANKS, ETC: 36.8

ANNUAL OPERATION PERIOD: 12. MONTHS

FERTILIZER VALUES IN SLUDGE:

NITROGEN EQUIVALENT: 32.8 TONS PER YEAR

PHOSPHORUS EQUIVALENT: 4.1 TONS PER YEAR

ANNUAL YIELD OF SNG: 8.318E 07 STANDARD CUBIC FEET OF METHANE

LIFE CYCLE COST ANALYSIS: (UTILITY METHOD)

PROJECT LIFE: 28 YEARS

COMPOSITE DISCOUNTING RATE: 11.18 PERCENT

ANNUAL EQUIVALENT OF INVESTMENT AND OPERATING EXPENSES: \$ 191151.

ANNUAL CREDIT FOR WASTEWATER TREATMENT : \$ 321288.

ANNUAL CREDIT FOR SNG PRODUCTION: \$ 14493.

ANNUAL CREDIT FOR FERTILIZER PRODUCTION:* \$ 8.

NET ANNUAL CASH FLOW: \$ 144542.

THE SYSTEM IS COST EFFECTIVE

* Fertilizer credit transferred internally

TABLE III-7
ALTERNATE ECONOMIC ANALYSIS

MUNICIPAL FINANCING METHOD

NO FEDERAL INCOME TAX

DEBT FINANCED BY MUNICIPAL BONDS AT 6.375 PER CENT

PROJECT LIFE: 20. YEARS

CONSTRUCTION PERIOD : 3 YEARS

TOTAL CAPITAL INVESTMENT : \$ 789583.

TOTAL ANNUAL O AND M EXPENSES: \$ 34579.

NONDEPRECIABLE INVESTMENT FOR LAND: \$ 17988.

EQUIVALENT ANNUAL EXPENSE : \$ 114269.

ANNUAL CREDIT FOR WASTEWATER TREATMENT: \$ 321288.

ANNUAL CREDIT FOR FERTILIZER PRODUCTION:* \$ 0.

ANNUAL PRODUCTION OF SNG: 3.18E B6 SCF

NET ANNUAL CASH FLOW: \$ 213285.

(BASED ON LOCAL GAS PRICE)

*Fertilizer credit transferred internally

TABLE III-8
SUMMARY OF SITE ANALYSES
CARBON-LIMITED CASE

Site	Wastewater Flow MGD	Pond Area Acres	SNG Production SCF/Year	Capital Investment Fall 1976 \$	Net Annual Cash Flow**	Normalized*
Bemidji	1.1	21	2.04×10^6	\$ 782,000	\$ 21,000	\$ 80,000
Caldwell	0.36	6	1.15×10^6	398,000	56,000	217,000
Chanute	1.1	22	2.65×10^6	786,000	150,000	132,000
Greenwood	2.1	46	6.71×10^6	1,203,000	504,000	212,000
Hammond	1.5	54	3.18×10^6	1,143,000	165,000	91,000
Jamestown	4.0	144	8.5×10^6	2,155,000	374,000	91,000
Kissimmee	1.3	20	4.15×10^6	814,000	300,000	220,000
Knoxville	17.0	487	5.42×10^7	5,883,000	4,619,000	203,000
Martinsville	2.5	62	7.98×10^6	1,395,000	612,000	211,000
Maysville	0.7	13	1.67×10^6	592,000	27,000	134,000
Minden	1.5	34	4.8×10^6	981,000	343,000	211,000
Natchitoches	1.8	40	5.75×10^6	1,100,000	421,000	211,000
Pensacola	6.0	101	1.91×10^7	2,279,000	1,602,000	218,000
Traverse City	1.8	38	2.87×10^6	1,087,000	131,000	50,000
Yazoo City	1.1	27	3.51×10^6	834,000	235,000	209,000

* Cash Flow for 1-MGD System at Site

** Municipal Financing Method

TABLE III-9
SUMMARY OF SITE ANALYSES
NITROGEN-LIMITED CASE

Site	Wastewater Flow MGD	Pond Area Acres	SNG Production SCF/Year	Capital Investment Fall 1976 \$	Net Annual Cash Flow* Fall 1976 \$/Year
Bemidji	1.1	42	3.32×10^6	\$ 1,227,000	\$ 29,000
Caldwell	0.36	13	1.87×10^6	600,000	27,000
Chanute	1.1	43	4.3×10^6	1,295,000	77,000
Greenwood	2.1	89	1.09×10^7	1,919,000	403,000
Hammond	1.5	105	5.17×10^6	1,821,000	73,000
Jamestown	4.0	279	1.38×10^7	3,640,000	363,000
Kissimmee	1.3	39	6.74×10^6	1,279,000	233,000
Knoxville	17.0	944	8.8×10^7	10,426,000	3,981,000
Martinsville	2.5	120	1.3×10^7	2,240,000	497,000
Maysville	0.7	26	2.72×10^6	916,000	35,000
Minden	1.5	65	7.8×10^6	1,549,000	261,000
Natchitoches	1.8	79	9.35×10^6	1,748,000	329,000
Pensacola	6.0	196	3.11×10^7	3,905,000	1,368,000
Traverse City	1.8	75	4.66×10^6	1,732,000	38,000
Yazoo City	1.1	53	5.71×10^6	1,308,000	168,000

*Municipal Financing Method

TABLE III-10
SUMMARY OF SITE ANALYSES
PHOSPHORUS-LIMITED CASE

Site	Wastewater Flow MGD	Pond Area Acres	SNG Production SCF/Year	Capital Investment Fall 1976 \$	Net Annual Cash Flow* Fall 1976 \$/Year
Bemidji	1.1	167	1.13×10^7	3,249,000	-150,000
Caldwell	0.36	51	6.4×10^6	1,479,000	-33,000
Chanute	1.1	175	1.47×10^7	3,395,000	-79,000
Greenwood	2.1	359	3.71×10^7	5,656,000	252,000
Hammond	1.5	422	1.76×10^7	5,130,000	-189,000
Jamestown	4.0	1127	4.71×10^7	11,277,000	-187,000
Kissimmee	1.3	156	2.29×10^7	3,529,000	-162,000
Knoxville	17.0	3806	3.0×10^8	35,900,000	3,495,000
Martinsville	2.5	482	4.42×10^7	6,689,000	342,000
Maysville	0.7	103	9.26×10^6	2,303,000	70,000
Minden	1.5	264	2.66×10^7	4,413,000	124,000
Natchitoches	1.8	317	3.19×10^7	5,033,000	183,000
Pensacola	6.0	789	1.06×10^8	12,065,000	1,270,000
Traverse City	1.8	300	1.59×10^7	4,958,000	-267,000
Yazoo City	1.1	212	1.94×10^7	3,515,000	57,000

*Municipal Financing Method

phosphorus-limited case has approximately eight times the acreage, while the treatment credit is only increased by 50 percent. Although the economy of scale reduces the capital increase to less than eight-fold, it is still much greater than the increased credit available.

Plant size is an important criterion for selecting an algae pond system site. Larger facility size results in an economy of scale in capital cost and a linear increase in the yield of sludge for fertilizing the Energy PlantationTM. As previously mentioned, there exists a point where the economy of scale ceases because of the problem of finding suitable level acreage. This is a site-specific problem which can not be addressed here.

The results of the site-specific performance runs indicate that, for the present, a carbon-limited, secondary treatment system will be most cost-effective. Any of the sites in the southeast, where 12 months' operation is possible, are cost-effective. A prime consideration is the availability of land and the availability of sufficient wastewater flow to produce a significant amount of fertilizer. If (1) construction costs can be reduced and (2) maintenance of blue-green algae cultures becomes technically feasible, it will then become possible and desirable to expand to the phosphorus-limited, tertiary treatment system. With this in mind, it will be necessary to select a site with flows and land requirements compatible with the phosphorus system. The data indicate that a flow of approximately 5 MGD would be a good demonstration size. Towns with wastewater flows larger than this would not have sufficient land for the phosphorus-limited system and towns with wastewater flows less than 5 MGD are not likely to be required to develop tertiary treatment facilities.

6. Research Needs

a. Major Cost Areas

The optimization and site-specific algae pond system computer runs

indicate that the highest net annual cash flow results from secondary treatment for BOD removal only. Development of a demonstration system to treat waste through the nitrogen-limited growth potential is valuable only insofar as it provides an opportunity to develop operational experiences with the ponds and carbonation systems. To make gas production from the phosphorus-limited system a cost-effective proposition, the operational ability to maintain a blue-green algae culture capable of fixing nitrogen must be developed. Present cost-estimates indicate that gas must sell for a 20-year average price of \$12.78/1000 SCF to be competitive with the carbon-limited wastewater treatment system. A 25 percent reduction in equivalent annual expenses results in the phosphorus-limited system becoming a cost-effective gas-producing operation.

Table III-11 gives a breakdown of annual costs and credits for both the carbon- and phosphorus-limited algae pond systems. On the expense side of the ledger, the annual equivalent of the pond construction cost represents 29 percent of the total annual equivalent expenses. It is therefore a major area for cost-reduction research. The next most important areas for cost reduction are the capital costs involved in harvesting and digestion of the algae. The annual equivalent expenses associated with these two areas represent one-fourth of the total annual expense of the algae pond systems for both the carbon- and phosphorus-limited cases. A third level of cost impact would be the capital expenses involved in the CO₂ flue-gas sparger system and the sand-bed sludge-drying systems.

On the credit side of the ledger, it is clear that the wastewater treatment credit is the most important factor. It will consequently be of utmost importance to determine a local wastewater treatment credit, i.e., the cost of the competing conventional system for a specific site. The annual credit is affected to a lesser extent by an improved gas yield. Increases in yield would result in a proportional increase in the gas

TABLE III-11
BREAKDOWN OF ANNUAL COSTS AND CREDITS*

<u>Cost Item</u>	<u>Annual Equivalent Expense</u>			
	<u>Carbon-Limited Case</u>		<u>Phosphorus-Limited Case</u>	
Growth Ponds				
Construction	\$ 33,000	29%	\$137,000	29%
O and M**	6,000	5%	19,000	4%
Harvesting				
Capital	7,000	6%	62,000	13%
O and M	3,000	3%	27,000	6%
Digester				
Capital	22,000	19%	50,000	11%
O and M	11,000	10%	17,000	4%
Spargers				
Capital	-----		41,000	9%
O and M	-----		25,000	5%
Sand Bed				
Capital	5,000	4%	24,000	5%
O and M	7,000	6%	36,000	7%
Interest on Land	1,000	1%	7,000	1%
Other	<u>19,000</u>	<u>17%</u>	<u>28,000</u>	<u>6%</u>
Total	\$114,000	100%	\$473,000	100%
<u>Annual Credits</u>				
Wastewater Treatment	\$321,000	98%	\$496,000	93%
SNG Production	<u>6,000</u>	<u>2%</u>	<u>35,000</u>	<u>7%</u>
Total	\$327,000	100%	\$531,000	100%

**Annual operating and maintenance expenses

*Calculations for a hypothetical 1-MGD system in Greensboro, N.C.

credit. An equivalent effect would result from increases in local cost of gas.

Increased fertilizer production would also improve the overall PEF economics. Because it involves a transfer of "product" between sub-systems, however, it does not represent a direct cash credit for the algae pond system analysis.

b. Specific Research Areas

Research areas fall into two basic categories: (1) development of technical data and operational experience and (2) development of less expensive process equipment or procedures. The growth ponds are a good example of this need for parallel research. On the one hand, it is necessary to develop operational experience with high-rate algal growth ponds to improve the solar conversion efficiency. Similarly, it is necessary to obtain operational experience with methods of maintaining blue-green algae cultures. This involves experimentation with hydraulic and solids recycle procedures. A parallel effort is necessary in reducing pond construction cost. Innovative pond arrangements are already being developed and low-cost technologies are being explored. The construction costs are primarily related to excavation, and hence, future research needs to be done on developing pond configurations with minimum excavation costs on land which is not level.

A similar parallel research effort is necessary on the flue-gas carbonation system. It is first necessary to study the effect of flue-gas carbon dioxide on the pond ecosystem. The Energy Research and Development Administration (ERDA) has already established contracts for this purpose. Assuming the carbon dioxide transfer proves feasible and no deleterious effects of trace materials in the flue gas are noted, it will also be necessary then to develop a low-cost sparging system. The sensitivity analysis indicates that the primary method of reducing cost in the sparging system is to improve its transfer efficiency. This may be done

using a series of baffles above this sparging system to increase contact time.

New technical and economic data are also required in the digestion step. It will be necessary to further quantify the effect of heating the digester to different temperatures. Also, a much clearer understanding of the mass flow and nutrient balances around the digester system must be developed. Finally, work has already been started on developing cost estimates for fermentation ponds, which would be much less costly than conventional tank digesters. These ponds would be equipped with floating gas domes which could be made of plastic. The potential cost-tradeoff between the lower capital cost and the anticipated lower gas yield (due to lack of mixing) must be studied.

While various harvesting procedures have been experimented with, none has a clear-cut advantage at this point in providing reliable, low-cost harvesting of algae. It seems clear that the method must be one that will require no chemical addition and will be capable of consistent removal efficiencies independent of algal species.

c. Development Approach

In all cases, it would appear that the most effective way of developing new technologies would be through small demonstrations of the entire algae pond system. In this manner the interaction of the various subsystems can be studied. For example: should algal species control be accomplished, microstrainers would then become a wholly suitable method of harvesting. Since, in many of the research areas, the development work is directed toward cost reduction of full-size equipment, it seems imperative to develop full-scale equipment for testing.

Table III-12 gives the relative incremental gas costs for the 15 candidate sites. The data indicate that cost-effective gas production is an attainable near-term goal. On this basis, a nitrogen-limited demonstration facility

would be invaluable (1) for providing pond and carbonation system operating experience and (2) for providing the research facility for species control techniques. Bearing in mind the land availability problem, a design flow of about 5 MGD seems advisable. Of the sites identified, Pensacola most nearly meets the guidelines for selecting a demonstration site. If sizeable industrial or seasonal waste loads were available, the other, smaller sites in the southeast would also be acceptable sites.

TABLE III-12
COMPARISON OF LOCAL GAS PRICES WITH PROJECTED
COST OF GAS PRODUCED BY ALGAE POND SYSTEM

<u>Site</u>	<u>Pipeline Natural Gas</u>		<u>Algae Pond System SNG</u> <u>20-year average price, \$/1000 SCF**</u>	
	Current Price \$/1000 SCF	Projected 20-year Average Price*	Nitrogen-limited Pond System	Phosphorus-limited Pond System
Bemidji	1.19	3.10	50.78	27.31
Caldwell	1.10	2.87	41.66	18.10
Chanute	0.69	1.80	44.85	19.75
Greenwood	1.10	2.87	25.24	9.40
Hammond	2.14	5.57	48.00	26.74
Jamestown	2.14	5.57	40.19	21.61
Kissimmee	1.15	3.00	26.92	9.41
Knoxville	1.00	2.61	19.79	5.57
Martinsville	1.78	4.64	24.80	9.23
Maysville	1.11	2.89	45.71	21.05
Minden	0.85	2.21	28.00	10.87
Natchitoches	0.85	2.21	26.39	9.96
Pensacola	1.15	3.00	20.67	4.97
Traverse City	1.43	3.73	53.33	32.08
Yazoo City	0.95	2.47	31.36	12.14

* The projected gas price for each of the next 19 years is calculated by assuming an annual inflation rate of ten percent. The present worth of each of these prices (based on 1,000 SCF) is calculated. The 20-year average price is equal to the uniform annual cash flow equivalent to the sum of the present worths.

** The average cost of producing SNG is the ratio of the change in the difference between treatment credit and equivalent annual expense to the change in annual gas production, i.e.

$$\text{Cost} = \frac{\Delta (\text{treatment credit} - \text{annual expense})}{\Delta 1000 \text{ SCF Units}}$$

based on a comparison with the carbon-limited case.

C. Energy PlantationTM Subsystems

1. Introduction

The purpose of this task was to develop a comprehensive techno-economic model for the Energy Plantation subsystem of the PEF.

The model is designed to enable:

- (1) estimating the cost of the plantation material (biomass) delivered at a given input for a given set of conditions (land, plants, field management, etc.);
- (2) optimization of land use for maximum biomass production or least cost of delivered biomass through the selection of the best combination of plants and field management techniques;
- (3) comparison of various situations such as new transportation technology, modifications to the field operation, etc.; and
- (4) design of an optimized plantation for given local conditions (land, weather, etc.) to achieve certain objectives such as the generation of certain amounts of biomass per year at the lowest possible cost.

In the Photosynthetic Energy Factory (PEF) context, the Energy PlantationTM model interfaces with several other parts of the PEF as indicated in Figure III-5. The purpose of the site-selection subroutine is to identify one or several sites for PEF use. For each of the sites identified and examined for evaluation, the site-selection subroutine supplies the land base data required for the Energy PlantationTM model.

The Energy PlantationTM model supplies the boiler-generator model with necessary input data such as quality and quantity of biomass, cost of delivered material, etc. The Energy PlantationTM model also interfaces with the Algae Pond subroutine, which provides input concerning the recycled materials (sludge and water essentially). Although the Energy

FIGURE III-5

INTERFACING BETWEEN THE ENERGY PLANTATION MODEL AND OTHER
SUBSYSTEM MODELS OF PEF

PlantationTM model described below will be used in the PEF context, it is designed to be self-sufficient; i.e., it can be used in situations different from those encountered in the PEF cycle. One such application is, for instance, the generation of feedstock for industries.

The block diagram of the Energy PlantationTM model is shown in Figure III-6 where the interdependence of the various subroutines is indicated.

(1) Land Resources

This block contains the input data concerning the land selected for establishment of a plantation, such as total area available for plantations, number and size of parcels, geographic distribution, regional climatic and soil data, and land cost. This input is used in Subroutine 4--species selection, Subroutine 7--field operation, and Subroutine 9--cost estimates.

(2) Base Data on Plants

This subroutine is a data bank that includes a list of potential candidates for Energy Plantations; sycamore (platanus occidentalis L.), hybrid poplar varieties (populus Tristis #1, populus hybrids clone NE-49, NE-252, NE-388), cottonwood (populus deltoides Bart; and Missouri and Sioux Male varieties of Populus deltoides), silver maple (acer saccharinum L.), black cottonwood (populus trichocarpa Torr & Gray) and eucalyptus (E. Grandis). Each species is characterized by its preferred soil and climate and by growth parameters. The functional dependence of the growth parameters on operational parameters, such as planting density, level of field management, soil quality, etc., is included as part of the characterization of the species. The input from this subroutine is used in Subroutine 4--species selection and characterization, and Subroutine 7--field operations.

(3) Recycling Inputs - Nutrient Balance

The PEF concept involves the recycling of by-products (ash, sludge, water) to the plantation. This subroutine estimates the amount of nutrients from outside sources to supplement the recycled input in order to maintain the plantation productivity. These values are then used in the cost-estimate subroutine to evaluate the cost of nutrients.

FIGURE III-6
BLOCK DIAGRAM OF ENERGY PLANTATION COMPUTER MODEL

(4) Species Selection and Characterization

Potential candidates to be grown in the plantation are selected from the list of plants considered for biomass production. The selection is made on the basis of inputs from Subroutine 1. Each species selected is characterized by its growth parameters, recommended field management, heating value, etc.

(5) Plant Growth Model

For each of the species selected in Subroutine 4, this subroutine will suggest yield-cycle combinations, expressed as oven-dry tons per acre-year, for a certain planting density and a given harvesting cycle. The corresponding required cultural practices will also be mentioned.

(6) Data Base for Field Operations

This data bank characterizes the equipment to be used in the field operations. The description includes capacity of equipment, investment, operating, maintenance and repair costs, operating labor and labor costs, and fuel type and consumption.

(7) Field Operations

The objective of this subroutine is to define the scheduling, equipment inventory, labor force, installation and start-up operations required for each of the yield-cycle combinations suggested as a result of Subroutine 5. Inputs include yield-cycle combinations from Subroutine 5, land areas and distribution from Subroutine 1, physico-chemical and other characteristics from the plant data base, nature and amounts of recycled materials from Subroutine 3 and base data concerning the field equipment and operations from Subroutine 6.

(8) Data Base for Cost Estimates

This data base supplies all costs and other financial data not supplied in other subroutines and necessary to perform the cost estimates.

(9) Cost of Biomass

This subroutine estimates the revenue required or cost of biomass per oven-dry ton or per million Btu delivered at the point of use. Inputs are supplied from Subroutines 1 (land costs), 6 (costs of equipment and labor), 8 (financial data) and 7 (labor and equipment inventory).

2. Description of the Subroutines

Each subroutine is described in turn and the supporting technical data are presented in Appendix C.

(1) Land Resources

a. Input Data Sheet

Except for very unusual situations, a plantation will be made of a number of parcels of various sizes and shapes distributed over a certain geographic area. Strictly speaking, the plantation model should consider each of these parcels individually, taking into account their relative locations and distances to the point of use of the biomass, as well as their soil characteristics. Such a detailed study is beyond the scope of the present model. Land distribution will be taken into account in the simplified way described below.

The plantation is assumed to be made of N parcels (PAR) of identical area included within a rectangular geographic area (GA) of given length (L_g) and width (W_g). Each parcel is further supposed to be a rectangle having the same length-to-width ratio as the geographic area (see Figure III-7). The number of parcels, the average parcel size, the geographic area and its length and width are all inputs supplied by the site-selection routine. A plantation density (PD) is defined as the ratio of the plantation area to the geographic area in which the parcels are included. During the field operations, equipment has to be moved from parcel to parcel. One can define an average total travel distance per parcel (TDP). Each parcel is assumed to be surrounded by a geographic area of similar shape (see Figure III-8) and the (TDP) is twice the distance from a corner of the geographic area to a corner of the parcel.

FIGURE III-7

SCHEMATIC DESCRIPTION OF THE LAND RESOURCES MODEL
(Simplified Case)

Geographic area = (GA) = $640 L_g W_g$ (acres)

Total Area of Plantation = (TAP) = $N(\text{PAR})$ (acres)

Area of a parcel = (PAR) (acres)

Total number of parcels = N

Plantation density = (PD) = $(\text{TAP})/(\text{GA})$

L_g = length of geographic area including the plantation (miles)

W_g = width of geographic area including the plantation (miles)

$g = L_g/W_g$

The method of estimation of (TDP) is described on Figure III-8. The data required to characterize the plantation land is listed in Table III-13 (items 1.1 to 1.4).

The proposed plantation area is further characterized on the basis of land quality. First, the forest group and section (FOG) in which the land is located is reported (see Subsection 4 for a discussion of the use of Forest groups). Then the land class and subclass describing the land are mentioned (items 1.5 to 1.7). In the approximation considered here, it is assumed that all the land considered for the plantation is of the same type. This method of characterizing the land by a weighted average land class is described in Appendix C.

The land proposed for Energy PlanationTM use is characterized by its cost (\$/acre-item 1.0). It is assumed that an average price per acre may be used for all plantation land in the area of interest. This input is supplied by the site-selection routine. The value quoted is the average value of farmland with buildings in the counties considered for plantation applications and thus includes a mix of land areas of various land classes and productivities. It is thus a good order of magnitude for land cost in the region and, if anything, is probably on the high side for plantation land cost.

The next item, 1.9, number of days in the growing season, is the frost-free period in the region of interest. This input is mostly used in determining the scheduling of field operations (Subroutine 7). The next four entries in Table III-13 (1.10 to 1.13) state the number of cultivation operations required during the growing season to ensure weed control in areas of the plantation harvested at various periods of the year. Areas harvested the previous year will regrow from their stumps as soon as the growing season starts and will thus require little weed-control cultivation. On the other hand, areas replanted in early spring will require the most weed-

FIGURE III-8

ESTIMATE OF AVERAGE TRAVEL DISTANCE PER PARCEL

Average travel distance per parcel = (TDP) $\approx d_1 + d_2 = 2d_1$

$$d_1 = \frac{l_g}{2} + \left(\frac{w_g - w}{2} \right) = \left(\frac{g+1}{2} \right) (w_g - w)$$

$$w_g = w/\sqrt{PD}$$

$$(TDP) = (g+1) w [(PD)^{-1/2} - 1] \text{ (miles)}$$

TABLE III-13
DATA INCLUDED IN SUBROUTINE 1: LAND RESOURCES

<u>Reference Number</u>	<u>Symbol</u>	<u>Description</u>	<u>Units</u>	<u>Reference to Call⁽¹⁾</u>
1.1	PAR	Size of identical parcels	acres	Input
1.2	N	Number of parcels in plantation	-	Input
1.3	L _g	Length of geographic area including plantation	miles	Input
1.4	W _g	Width of geographic area including plantation	miles	Input
1.5	FOG	Forest group and section	-	Input
1.6	CLA	Average land class of the planta- tion	-	Input
1.7	SUCLA	Land subclass of the plantation	-	Input
1.8	LACOST	Average cost of land in plantation region	\$/acre	Input
1.9	DGS	Number of days in growing season	days	Input
1.10	C ₁	Number of cultivations per acre harvested in August to March	-	Input
1.11	C ₂	Number of cultivations per acre harvested in May to June	-	Input
1.12	C ₃	Number of cultivations per acre harvested in July to August	-	Input
1.13	C ₄	Number of cultivations per re- planted acre	-	Input
1.14	NSLU	Nitrogen returned from sludge	T/year	Input
1.15	PSLU	Phosphorus returned from sludge	T/year	Input

control cultivation. These inputs are determined on the basis of local growing and soil conditions and are thus a site-specific input.

Items 1.14 and 1.15 are inputs supplied by the algae pond model which state the amount of nitrogen and phosphorus returned to the plantation through recycling of the sludge.

b. Approximations

The approximations introduced in this subroutine relate mostly to the characterization of the plantation land. Specifically, it is assumed that the plantation land is made of identical parcels distributed regularly within a certain geographic area, that the plantation land is characterized by an average weighted land class and that the land cost is the average cost of farm land (with buildings) within the region of interest. The impact of these approximations on the overall fuel costs will be discussed in a later section.

(2) Base Data on Plants

This subroutine is essentially a data bank describing the growth characteristics of species retained for Energy PlantationTM applications. The method of characterization of plant survival and plant growth is described in Appendix C.

a. Data Sheet Format

Table III-14 shows a typical data sheet for a candidate species for the Energy PlantationTM. A few comments concerning some of the entries are made below:

- the first three entries, FOG, CLA, SUCLA, list the forest group(s), land class(es) and subclass(es) in which the species is known or expected to grow well,
- the fourth entry, TREAT, lists the cultural treatments required by the species to display the growth characteristics described further

TABLE III-14
DATA INCLUDED IN SUBROUTINE 2: DATA SHEET FOR A SPECIES

<u>Reference Number</u>	<u>Symbol</u>	<u>Description and Equation</u>	<u>Units</u>	<u>Reference to Call</u>
5.	SPE	Name of species	-	Input
5.1	FOG	Forest group in which species is known to grow	-	Input
5.2	CLA	Classes of land in which species is known or expected to grow	-	Input
5.3	SUCLA	Subclasses of land in which species is known or expected to grow	-	Input
5.4	TREAT	Cultural treatments required to obtain the yields quoted	-	Input
5.5	LOC	Location of the experimental plots where the data was generated	-	Input
5.6	LAND	Class of land on which data was generated	-	Input
5.7	γ	Constant in expression of survival rate		Input
5.8	δ	Exponent in expression of survival rate		Input
5.9	m_1	Exponent for first growth	-	Input
5.10	α_1	Growth parameter for 1st growth	$\frac{\text{o.d. lb}}{\text{tree}-(\text{ft}^2)^{\beta_1}}$	Input
5.11	β_1	Plantation density dependence parameter for 1st cut	-	Input
5.12	κ_1	Growth limiting factor for 1st growth	$\frac{\text{year}^{-1}}{(\text{ft}^2)^{\lambda_1}}$	Input
5.13	λ_1	Plantation density dependence parameter for 1st growth	-	Input
5.14	m	Exponent for coppice growth	-	Input
5.15	α_2	Growth parameter for coppice growth	$\frac{\text{o.d. lb}}{\text{tree}-(\text{ft}^2)^{\beta_2}}$	Input

TABLE III-14 (Continued)
DATA INCLUDED IN SUBROUTINE 2: DATA SHEET FOR A SPECIES

5.16	β_2	Plantation density dependence parameter for 2nd cut	-	Input
5.17	κ_2	Growth limiting factor for 2nd growth	$\frac{\text{year}-1}{(\text{ft}^2)^{\lambda_2}}$	Input
5.18	λ_2	Plantation density dependence parameter for 2nd growth	-	Input
5.19	MAXAR	Maximum value of the planting area per tree A for which data is valid	$\frac{\text{ft}^2}{\text{tree}}$	Input
5.20	c	Number of clones per plant	-	Input
5.21	(FWR)	Fraction of total weight in roots	-	Input
5.22	h_1	Heating value of o.d. wood at first cut	Btu/lb	Input
5.23	h_2	Heating value of o.d. wood at coppice cut	Btu/lb	Input
5.24	h_3	Heating value of roots	Btu/lb	Input
5.25	(MC)	Moisture content - percent of o.d. weight	%	Input
5.26	(VCL)	Volume of clone	ft^3/clone	Input
5.27	(PIS)	Productivity index of land class		Input

- down on the data sheet. The cultural treatments considered include cultivation--CULT--for weed control and site improvement, fertilization--FERT--for yield improvement and irrigation--IRR--which, so far, has not been included in the plantation model,
- the next two entries, LOC and LAND, indicate the location and land class of the experimental plots on which the data used to generate the present data sheet were recorded,
 - the next twelve entries, from γ to λ_2 , are the parameters used to describe survival and growth (original and coppice) of the species considered. The significance of these parameters is discussed in Appendix C,
 - MAXAR: this entry specifies the maximum value of the area per tree at planting (ft^2/tree) to be considered in subsequent subroutines. This value is set by the range of experimental points available to establish the data sheet (see Appendix C),
 - the next entry, c, states the number of clones which can be obtained from one plant in its first growth, i.e., when essentially one stem only is available for making cuttings. This assumes that the cuttings are made when the plants are two to three years old; this could be generalized to include plants of various ages,
 - (FWR) is the weight of the root system expressed as a fraction of the oven-dry weight of above-ground biomass. This factor is used to estimate the total biomass produced during a complete cycle; this includes the roots for the year during which the plantation is destructively harvested before replanting,
 - the next three entries, h_i , are the average heating values of oven-dry biomaterial for first and coppice growth of above-ground material and for roots respectively,
 - (MC) is the moisture content expressed as fraction of oven-dry weight,
 - (VCL) is the volume of a clone, ft^3 per clone,
 - (PIS) is the productivity index of the land class of the plot on which the experimental data for the species of interest was grown.

b. Data Sheets for Species of Interest for the Energy PlantationTM

Data sheets for several varieties of hybrid poplars (populus hybrids Tristis # 1, clones NE-49, NE-252 and NE-388), eastern and plains cottonwood (populus deltoides Bart. and Missouri and Sioux Male varieties), sycamore

(platanus occidentalis L.) grown under various conditions, silver maple (acer saccharinum L.), black cottonwood (populus trichocarpa Torr & gray) and eucalyptus (E. grandis) are included in the computer data bank. The degree of reliability of these data sheets is considered in Appendix C where the source, precision and method of interpretation of the original data are discussed.

c. Limitations

The limitations introduced in using the data sheets described above are those inherent to the model adopted to describe plant growth (see Appendix C). One of these is that the validity of the model is restricted to a range of planting densities characterized by MAXAR. Other uncertainties are introduced in the determination of the growth parameters from the experimental data. The impact of these uncertainties on the overall cost of the biomass produced will be discussed at a later point. It should however be stressed that the yields calculated from the growth model using the parameters of the data sheets are generally within about five percent of recorded experimental values. Such agreement is, in fact, well within normal yearly fluctuations in yield resulting from yearly variations in local climate.

(3) Recycling Inputs - Nutrient Balance

The inputs of this subroutine are the amounts of nitrogen and phosphorus recycled yearly from the algae pond to the plantation, as well as the amount of ash returned from the boiler. On this basis, the present subroutine estimates the amount of supplementary nutrients which has to be supplied yearly to maintain the productivity of the plantation.

a. Nutrient Balance

The amount of mineral nutrients removed through a harvest of biomass is estimated on the basis of published data for the content of minerals in the stem, branches and leaves of juvenile hardwoods (46 to 50). The estimate takes into account the duration of the rotation and distinguishes between the cases of harvest of the tree, including leaves, and harvest of stem and branches only.

The calculation of the amount of nutrients required to replace the harvested nutrients accounts for losses of nutrients from one application of fertilizer at the beginning of the rotation which are due to microbial degradation and ground-water leaching during the duration of the rotation. It also accounts for the same types of losses from the nutrients recycled each year as leaves die at the end of the growing season and decompose on the ground (the method of estimation of the nutrient requirements is discussed in Appendix C).

The expression for the N, P, K, and Ca needed to be added to compensate for the nutrients removed through harvests are, respectively:

$$[N] = 0.0011 (TPAY)(1.19)^{n_2-2} - (NSLU) \quad (\text{tons of N/year}) \quad (\text{III-2})$$

$$[P_2O_5] = (TPAY)[0.001475(1.033)^{n_2-2} - 0.00101(1.022)^{n_2-2}] - 2.2913 (PSLU) \quad (\text{III-3})$$

(tons of P_2O_5 /year)

$$[K_2O] = (TPAY)[0.00985(1.0423)^{n_2-2} - 0.00347(1.010)^{n_2-2}] \quad (\text{III-4})$$

(tons of K_2O /year)

$$[CaO] = (TPAY)[0.010475(1.0546)^{n_2-2} - 0.007556(1.022)^{n_2-2}] \quad (\text{III-5})$$

(tons of CaO/year)

where [] = amounts of nutrients to be supplied per year (ton of nutrient/year)

(TPAY) = total plantation annual yield (o.d.T/year)

(NSLU) = amount of nitrogen returned to the plantation from the sludge

(PSLU) = amount of phosphorus (P) returned to the plantation from the
sludge

n_2 = duration of coppice growth period (years).

The calculation assumes that 80 percent of the ash is returned to the plantation and that only CaO is supplied from the ash. There are indications, however, that some phosphorus and perhaps potassium could also be returned in this fashion, (30).

b. Limitations

The nutrient balance used here assumes that only one application of fertilizer is made per rotation, which will tend to increase the amounts needed to compensate for losses. Other methods of applications enabling a yearly application during the cycle should be considered. In the absence of enough data, it has been assumed that the only value of ash recycling is in supplying some of the required calcium and in improving soil texture. Finally, the water content of the sludge has not been accounted for since the analysis, so far, is restricted to land areas where rainfall is sufficient to support high plantation yields.

(4) Species Selection and Characterization Subroutine

Given the information supplied by Subroutine 1--Land Resources, the first objective of the present subroutine is to select the species to be retained as potential candidates for use in the plantation under study. This selection will be made among the species included in Subroutine 2--Base Data on Plants. The second objective is to characterize the growth potential of the selected species; i.e., the typical growth parameters quoted in the Data Base are adjusted to take into account the local soil characteristics.

a. Plant Selection Procedure

The first level of selection of the species to be used at a plantation site is performed on the basis of Forest Regions and Sections as defined by Braun for the eastern part of the United States (31). Within the eastern United States, Braun has defined nine forest regions (1 to 9) each including subsections (a, b, c). This classification was established on the basis of observation of occurrence and/or observation of indigenous species within the region considered. Thus, the classification reflects the influence of natural selection over many years and suggests for each region species or groups of species which are well adapted to the site considered. The classification considers "natural" species such as oak, maple, etc.. Hybrids or imported species may also be assigned to various groups as, often, hybridization has been performed to create a

variety adapted to a particular area of the United States. Braun's study includes only the eastern United States. A similar approach can be followed for the western states using the forest types as defined by the U.S. Forest Service as a basis (32). Thus, the first step in the selection procedure is, given a site located within one of the forest regions, to pick all the species within the data bank which are recognized as potential candidates for growth at the plantation site. The various forest regions and sections for the eastern United States are shown on Figure III-9.

A potential plantation site located within a certain forest region will be made of land of various types, abandoned farm land, occasionally flooded bottom land, rocky slopes, etc. Different species will be best adapted for each type of land, and thus within the group of species selected for the forest region considered, it is necessary to further refine the choice to those species which will do best for the land available for plantation applications. The various types of land involved are characterized on the basis of the classes adopted by the Soil Conservation Service of the U.S. Department of Agriculture in its national inventory of soil and water conservation needs (8). The method of land characterization is described in Appendix C. Given the land class and subclass characterizing the plantation land (input from Subroutine 1), the computer routine will select among the species retained on the basis of those forest groups species which grow best in soils having the land classes of the plantation land considered. The overall selection process sequence is described in Figure III-10.

b. Productivity Weighing Factors

The parameters, α_i , β_i , x_i , λ_i used in the data bank to describe plant growth (see Table III-14) were determined from experimental data recorded for each of the species considered. Experimental data were generated on plots of land having specific characteristics, soil, climate, etc. The land considered for plantation application may not have the same growth

Figure III-9: Forest Regions and Sections (Eastern U.S.)

1. Mixed Mesophytic Forest Region
2. Western Mesophytic Forest Region
3. Oak-Hickory Forest Region
4. Oak-Chestnut Forest Region
5. Oak-Pine Forest Region
6. Southeastern Evergreen Forest Region
7. Beech-Maple Forest Region
8. Maple-Basswood Forest Region
9. Hemlock-White Pine Northern Hardwoods Region

From: E. L. Braun, "Deciduous Forests of Eastern North America"

FIGURE III-10

SPECIES-SELECTION PROCESS

potential, and it is thus necessary to adjust the yields predicted on the basis of the experimental data to take into account the difference in productivity potential between the experimental plots and the potential plantation land.

This weighting of productivity potential is based on the use of the productivity index of various classes of land as defined by the Soil Conservation Service of the U.S. Department of Agriculture, (8). Following this approach, a land-use index can be associated with each class of land which reflects the relative potential return of land of various classes for which identical cultural management has been applied. For instance, land of Class 3 has an index of 100, while land of Class 1 has an index of 150. This means that all cultural practices being identical, land of Class 1 will generally produce 50 percent more crop value than land of Class 3. It was shown (see Appendix C) that productivity ratios similar to those generally observed for agricultural crops can be expected from deciduous tree crops grown on corresponding classes of land. The productivity scale based on land classes follows closely the scale based on site indexes used in forestry, once a correspondence has been established between the land classes and site indexes scales.

The productivity-weighting procedure is as follows:

- determination of the "average weighted land class" (AWLC) of the land considered for the plantation,

$$(AWLC) = \frac{\sum_i (LA)_i \times (PI)_i}{\sum_i (LA)_i} \quad i = 1 \text{ to } 7 \quad (III-6)$$

where $(LA)_i$ = land area of class_i available for plantation use, (acres). These data are available on a county basis for the entire United States (8). In the summation, land of Class 8 is not considered as generally unsuited for plantations (slopes, mountain sides, etc),
 $(PI)_i$ = productivity index as defined by Reference 9. This average weighted land class is an input listed under land class (CLA) in Subroutine 1, Land Resources.

- determination of the productivity index of the land class of the plot on which the experimental data for the species of interest were generated, thus

$$(PIS) = 1.73571 - 0.23393 (LAND) \quad (III-7)$$

where (PIS) is the productivity index for the species of interest for the plot on which the data were generated,

(LAND) is the class of land on which the experimental data reported in the data sheet were generated, (see data sheets in Subroutine 2)

The method used to derive equation (III-7) is discussed in Appendix C.

- determination of the productivity weighting factor for the species of interest (PWF) for the site considered for plantation use,

$$(PWF) = \frac{(AWLC)}{(PIS)} \quad (III-8)$$

For each species considered in Subroutine 5--plant-growth model--the productivities determined on the basis of the data sheet of Subroutine 3 are multiplied by (PWF) to take into account the differences in land qualities between the site of the plantation and the site at which the experimental data were generated.

c. Limitations

The species-selection procedure based on the forest groups is a good method of choosing species adapted to the local soil types. At the present state of development of the model, this procedure is probably quite adequate.

The productivity-weighting-factor approach to relating the plantation productivity to land quality is a global method which has proven to be adequate for comparison of agricultural land parcels within a geographic area.

This method does not, however, take explicitly into account climatic differences between locations and, in particular, between the plantation site and the site at which the growth data was generated. Methods taking into account climatic and soil factors have been proposed (33 , 34). InterTechnology's analysis of the problem (6), however, has shown that in most cases, for species well adapted to the plantation location, conflicting climatic factors often reduce the expected productivity of apparently climatically favorable sites.

(5) Plant-Growth Subroutine

The purpose of this subroutine is to estimate the average sustained yield (oven-dry tons/acre-year) over a full plantation cycle for given field management conditions (age at first and second harvests, number of harvests, etc.)

a. Method

The average sustained yield $\bar{Y}$ from a planting in a plantation from which a succession of harvests have been taken during a period of $\sum n_i$ years is given by

$$\bar{Y} = \frac{1}{\sum n_i} (Y_{n_1} + Y_{n_2} + Y_{n_3} + \dots) \quad (\text{o.d. tons/acre-year}) \quad (\text{III-9})$$

where $\sum n_i$ = total number of years elapsed between the time the stand was planted and the time the last harvest is taken from the stand, before it has to be replaced by a new planting,

n_i = years of growth before the i^{th} harvest

Y_{n_i} = yield of the i^{th} harvest resulting from a growth period of n_i years - o.d. tons/acre.

The yield from each harvest Y_{n_i} is given by:

$$Y_{n_i} = N_{n_i} y_{n_i} / 2,000 \quad (\text{III-10})$$

or

$$Y_{n_i} = \left(\frac{N_{n_i}}{2,000} \right) y_{\infty} \left[1 - e^{-\left(\frac{n_i}{n_0} \right)^m} \right] \quad (\text{o.d. tons/acre}) \quad (\text{III-11})$$

where N_{n_i} = number of living plants per acre at year n_i (plants/acre)

y_{n_i} = yield per living plant at year n_i (o.d. lb/plant)

y_{∞} = asymptotic yield (o.d. lb/plant);

n_0 = limiting factor (years)

m = growth power

The values of y_{∞} , n_0 , and m depend on whether the harvest considered is a first or a coppice harvest.

Two assumptions are introduced at this point:

(1) The number of surviving plants N_{n_i} at the second and subsequent harvests is equal to the number of surviving plants after the first harvest, thus

$$N_{n_1} = N_{n_2} = N_{n_3} = \dots \quad (\text{III-12})$$

(2) The harvestable yields per plant from second and subsequent (coppice) harvests are equal provided the intervals between harvests are equal, thus

$$y_{n_2} = y_{n_3} = \dots \quad \text{if } n_2 = n_3 = \dots \quad (\text{III-13})$$

With these assumptions, equation (III-11) becomes

$$\bar{Y} = \frac{N_{n_1}}{\sum_{i=1}^{m+1} n_i} (y_{n_1} + \sum_{i=2}^m y_{n_i}) \quad (\text{o.d. tons/acre-year}) \quad (\text{III-14})$$

where m = number of coppice harvests taken after this first harvest.

For the particular case in which all second and subsequent harvests are taken at equal intervals, n_2 years, equation (III-11) becomes:

$$\bar{Y} = \frac{N_{n_1} (y_1 + M y_{n_2})}{(n_1 + M n_2) \times 2,000} \quad (\text{o.d tons/acre-year}) \quad (\text{III-15})$$

b. Yield Subroutine

A complete program was written to perform the yield estimates on the basis of the method described in a. above. The program estimates values of annual sustained yields in accord with equation (III-14) for various combinations of planting densities and harvesting cycles for the species retained through Subroutine 4--Species Selection. As indicated in Section (4), the annual sustained yield determined from equation (III-14) is multiplied by the productivity weighting factor (PWF--equation (III-8)) to take local soil quality into account.

The output of the program is an estimate of that combination of planting density and harvest schedules which maximizes the average annual sustained yield. The program also identifies any combinations of planting density and harvest schedule which can be expected to produce at least 95 percent or at least 90 percent of the maximum yield. These outputs are provided because combinations of planting density and harvest schedules may exist which provide sustained yields almost as large as the maximum possible yield but at less cost. For instance, some of the "almost-as-good" yields may require a lower planting density (thus lower planting costs) or less frequent harvesting (hence possible lower field costs).

Figure III-11 shows a typical printout from Subroutine 5. The items included are:

FIGURE III-11

TYPICAL PRINTOUT OF SUBROUTINE 5 - PLANT-GROWTH SUBROUTINE

MISSOURI COTTONWOOD-M

FOREST GROUP AND SECTION: 6A

LAND CLASS: 4

LAND SUBCLASS:

TREAT: CULT

LOCATION: KANSAS

LAND: 3

5 ENTRIES ABOVE 0.95 * MAXIMUM

ENTRY	A	N1	N2	M	SURV	YIELD1	YIELD2	PCYDU	ASY
1	4	2	2	5	9397.	9.7164E-01	4.7596E 00	12.	7.5037E 00
2	6	2	3	5	6433.	1.3284E 00	9.7678E 00	17.	7.3410E 00
3	8	2	3	5	4902.	1.6137E 00	1.2793E 01	17.	7.3153E 00
4	12	2	3	5	3964.	1.8975E 00	1.5606E 01	17.	7.2105E 00
5	4	2	3	5	9397.	9.7164E-01	6.5042E 00	17.	7.1621E 00

- name of species (Missouri Cottonwood, in the case of Figure III-11)
- forest group and section to which the land considered for the plantation belongs (6a in the case of the figure)
- land class characterizing the plantation (4 in the case considered)
- land subclass characterizing the plantation (in the case considered, no particular subclass could be assigned to the plantation area)
- TREAT: cultural treatment required to achieve the growth characteristics of the species considered reported in the data bank of Subroutine 2
In the case considered, cultivation for weed control is required.
- location of the site at which the data was generated (Kansas in this case)
- land is the land class of the site at which the data was generated (3 in this case). Based on the discussion of Section(4), the productivity weighting factor (PWF) to be used to determine the sustained yields at the proposed plantation site is thus (equation (III-8)):

$$(PWF) = \frac{(AWLC)}{(PIS)} = \frac{1.73571 - (0.23393) \times 4}{1.73571 - (0.23393) \times 3} = 0.77$$

This factor is applied to the yields reported in the lower part of the figure for various harvesting cycles.

The lower part of the printout lists the planting and harvesting cycles retained for further analysis. The data supplied for each case includes:

- A: area per tree at planting (ft²/tree)
- N₁: age at first harvest (years)
- N₂: deviation of coppice growth between coppice harvests (years)
- M: number of coppice harvests
- SURV: number of surviving plants at time of first harvest
- YIELD 1: yield per tree at time of first harvest (o.d. lb/tree)
- YIELD 2: yield per tree at time of coppice harvests (o.d. lb/tree)
- PCYDU: plantation cycle deviation - N₁ + M x N₂ - (years)
- ASY: annual sustained yield (from equation (III-14)) corrected by production weighting factor - (o.d. tons/acre-year).

These data constitute the major input to Subroutine 7--field operations.

c. Limitations

The major approximations introduced in this subroutine are:

- the selection of equations of the form $y_{\infty} \left(1 - \exp \left[- \left(\frac{n_i}{n_0} \right)^m \right] \right)$ for the description of plant growth. This problem is addressed in some detail in Appendix C,
- the assumption that the number of living stumps remaining in the plantation after the first harvest remains constant for a number of subsequent harvests (equation (III-12)). It is expected that some stumps will disappear through damage or weakening, through harvesting, decay, etc. As this occurs, the neighboring stump will have more growing space and thus produce more biomass per stump (see Appendix C). Thus the product of the number of stumps by the amount of biomass generated per stump will tend to remain constant. Data for sycamores in Georgia (35) support this assumption.
- the assumption that the yields from coppice growths are constant for several coppice harvests. It has been observed that the first coppice harvest, while significantly larger than the first harvest, may not be as large as subsequent coppice harvests (35). After this first coppice harvest, however, the full productivity potential appears to be reached and maintained for several subsequent coppice crops. The number M of successive coppice harvests which can be reaped from a planting is an important parameter in the concept. Discussions with various consultants suggest that with adequate management a value of five would be assigned to M.

(6) Data Base for Field Operations Subroutine

This data bank describes and characterizes the equipment and buildings used for the operation of the plantation and thus constitutes the data base for Sub-routines 7--field operations--and 9--cost of biomass. The equipment listed in the data bank is grouped in broad categories:

- harvesting
- transportation
- cultural practices
- land clearing and road maintenance

- nursery operations and replanting
- motor pool
- supervision

Two additional categories are included:

- plantation preparation and installation
- plantation start-up

The data included in these last two categories characterize the operations required to bring the plantation to full operation.

For presently used equipment, the characteristic data were obtained from suppliers of the machinery or from agricultural consultants (36). The performance characteristics are thus up-to-date, and the prices used are as of early 1977. For new machinery or machinery in the R & D stage, performances and costs have been assumed after discussions with potential suppliers and agricultural consultants. The latter characteristics thus involve a certain degree of uncertainty which could affect the final results.

a. Equipment included in the data bank

Equipment and machinery included in the data bank are grouped and listed following the categories of operations mentioned above.

- Harvesting

No continuous harvester for young trees of the type assumed here exists at present. Experiments conducted in Georgia (37) have shown that a standard forage corn harvester-chipper can cut and chip young sycamores (2 years old - about 2 inches in diameter). The harvester considered here is an extension of this standard machine, reinforced to harvest young trees rather than the softer corn stalks. A four-row harvester-chipper having a capacity of sixteen green tons per hour and a base price of about \$105,000 is assumed in the data bank. These characteristics, as well as maintenance, fuel consumption and repair characteristics were adopted after discussions with potential manufacturers of the equipment (29). It should be noted that the performance (tons chipped per hour) and fuel consumption (gal/hour) of this hypothetical harvester are very similar to those of whole tree chippers presently in use (51).

- Transportation

The equipment for the transportation of wood chips from the field to the point of use included in the data bank consists of:

- tractor-trailer units
- field tractors with dump wagons
- pneumatic tube system.

The two first pieces of equipment are standard commercial items for which a choice of capacities is available. The pneumatic system has been tested for about five years in the United States and is presently used commercially in Japan. The transportation equipment listed above is used in various combinations in the field operations subroutine.

- Cultural practices

The equipment included in this category is heavy-duty agricultural machinery:

- disks
- sprayers (fertilizer or sludge and fungicide)
- tractors

It has been assumed that spreading the sludge returned from the algae pond is done by the transportation units, some of which are equipped with spreading devices similar to standard manure spreaders.

- Land clearing and road maintenance

Land clearing prior to replanting at the beginning of a plantation cycle and normal field road maintenance is performed by heavy-duty crawlers in standard forestry practice.

- Nursery operations and replanting

This category of field operations requires the following items:

- dump wagons and tractors (for clone material collection)
- cutting tools for clone production
- underground cement-block storing rooms

- working area (metal building for instance)
- packing equipment
- planter--large capacity, four-row planters are considered in this case. Such units have been used on an experimental basis (38).

- Motor pool

The following equipment is included for motor pool operations:

- work area (building) with maintenance equipment (bridge, etc)
- small tools and supplies
- inventory of replacement equipment if included in the operation
- fuel tank trucks for field resupply of machinery

- Supervision

The equipment required for the supervising function includes:

- office space
- office supplies
- communication equipment
- pick-up trucks

- Plantation preparation, installation and start-up

These operations are performed before the plantation has reached its full operation stage. As all the personnel and equipment has not been gathered at that stage, it is assumed that the required tasks are subcontracted to local operators. Thus, the data bank lists unitary costs of the various operations required to install and start the plantation. Supplies such as the initial planting material (clones or seedlings), fertilizer, etc. are also listed in the data bank.

b. Characterization of the equipment

Each piece of equipment included in the data bank is characterized by the following items:

- rate of operation (acres cultivated per hour, green tons harvested per hour, etc.);
- velocity (miles per hour);

- utilization load factor. This factor is introduced to take into account losses of operating time due to changes of shifts, refueling, minor mechanical adjustment, etc.;
- fraction of operating time required for maintenance and repair. When the plantation operation includes sufficient replacement units, this factor is zero;
- manpower required per operating shift. A cultivator requires one tractor driver while a four-row replanter requires one driver plus four field hands for planting, for instance (man-year per full year-long shift);
- number of shifts included in operation. Some operations, such as harvesting or cultivation may be performed on the basis of three eight-hour shifts per operating day, while some others may be restricted to one or two shifts per day;
- cost of machinery (\$/per unit);
- depreciation period (hours or years);
- cost of maintenance and repair per hour of operation (\$/hour);
- type of fuel used (gasoline or diesel);
- fuel consumption per hour of operation (gal/h);
- operator cost (\$/man-year);
- number of days of operation (days/year). This number is generally a site-specific item. For instance, over-the-road transportation is limited by climatic conditions (snow, ice) while harvesting may be limited by climatic factors (field conditions, growing season) and by biological factors (early growth after the dominant season, risk of fungae propagation, etc.); and
- number of hours of operation per day (h/day). This item is related to the previously considered item: number of shifts included in the operation. It is a site- and operation-specific item.

As indicated above, the data bank for the plantation installation and start-up quotes unitary costs for the various field operations required rather than equipment costs and characteristics.

c. Uncertainties

The major uncertainty in the data included in Subroutine 6 is that concerning

the harvester. This machine is a major component of the plantation operations, and the impact of variations in performance characteristics on the overall cost of the biomass produced will have to be estimated.

Other types of equipment are essentially standard or slightly modified agricultural units for which performances are well established.

(7) Field Operations Subroutine

The field operations subroutine includes the following items:

- plantation management and yield
- field operations
- nursery operations
- supervision
- motor pool operations
- plantation preparation and installation
- plantation start-up

This set of items is analyzed for each yield-cycle combination recommended as a result of Subroutine 5. Each item is considered in succession below.

a. Plantation Management and Yield

For each species selected in Subroutine 4, Subroutine 5 lists a number of yield-cycle combinations to be considered for the plantation. These combinations are characterized by the planting area per tree, $A(\text{ft}^2/\text{tree})$, the ages at first and coppice harvests, n_1 and n_2 (years); the yields per tree at first and coppice harvests, y_1 and y_2 (o.d. lb/tree); the number of successive coppice harvests taken from the plantation, M ; the deviation of a complete plantation cycle, $(\text{PCYDU}) = n_1 + Mn_2$ (years); and the average annual sustained yield for a full plantation cycle, (ASY) (o.d. T/acre-year). These data as well as the data from Subroutine 6 are the inputs to Subroutine 7.

The total plantation area is divided in $(n_1 + Mn_2)$ equal planting units (PU), (acres). Each year, M planting units reaching the end of their coppice growth period (age n_2) and one planting unit reaching the end of its first growth period (age n_1) are harvested. Also, each year one planting unit, from which the M^{th} coppice harvest has been taken, is destructively harvested (land cleared) and replanted. The replanting material (clones) is generated from the material harvested in the planting unit having reached the end of its first period of growth. The effective annual yield of the plantation is thus equal to the material harvested minus the fraction of the biomass required to produce clones for replanting plus, eventually, the roots from the planting unit being cleared at the end of a complete growth cycle if the roots can be effectively recovered. The plantation management schedule is illustrated in Figure III-12 for a hypothetical case in which $n_1 = 2$, $n_2 = 2$, and $M = 5$. It should be stressed that this scheduling enables continuous and, in principle at least, perpetual operations.

For each species-yield-cycle combination, the plantation management schedule is characterized by the following data reported in the final printout:

- (PU) = planting unit

$$= N (\text{PAR}) / (n_1 + Mn_2) \text{ (acres)}$$
 (See Table III-13 for definition of N and (PAR))
- R = plants to be harvested to replant one acre of plantation

$$= 43,560 / \text{Ac} \text{ (plants/acre)}$$
 (See Table III-14 for definition of c)
- (TPAY) = Total plantation annual yield

$$= \frac{N_{n_1} (\text{PU})}{2,000} \left[\left(1 - \frac{R}{N_{n_1}}\right) y_1 + [M + (\text{FWR})] y_2 \right] (\text{PWF}) \text{ (o.d. T/year)}$$

where (FWR) is the fraction of material in the roots (see species data sheet-Table III-14)

(PWF) is the productivity weight factor (see Section (4) b.)

FIGURE III-12

PLANTATION MANAGEMENT SCHEDULE

Case: $n_1=2$, $n_2=2$, $M=5$ (hypothetical situation)

Plantation unit in growth.

Plantation unit harvested at the end of a coppice growth period (age n_2).

Plantation unit harvested at end of first growth period (age n_1)

Plantation unit destructively harvested at the end of a coppice growth period to be replanted in order to initiate a new complete cycle.

- (TPAEY)= Total plantation annual energy yield

$$= N_{n_1} (PU) \left[\left(1 - \frac{R}{N_{n_1}} \right) y_1 h_1 + [Mh_2 + (FWR)h_3] y_2 \right] (PWF) \text{ (Btu/year)} \quad (III-16)$$

where the h_i ($i=1,2,3$) are the heating values of first and coppice above-ground material and roots, respectively (Btu/o.d. lb)
(See species data sheet-Table III-14)

Figure III-13 shows the part of a typical printout in which the plantation management scheduling is reproduced for a species-yield-cycle combination. The part of the printout above the line defining the species-yield-cycle combination shows the general data characterizing the plantation and obtained on the basis of the input of Subroutine 1 (see Table III-13).

b. Field Operations

The field operations considered here include:

- harvesting
- collection and transportation of the biomaterial and spreading of the recycled materials (ash, sludge)
- cultivation
- fertilization
- fungicide application
- land clearing, road work
- replanting
- clone material production

For each of the field operations listed above, the computer program estimates:

- the total working hours required yearly to perform the operation considered,
- the total travel time (hours) required to move the equipment from parcel to parcel,

PART OF THE COMPUTER PRINTOUT DESCRIBING PLANTATION MANAGEMENT SCHEDULING
AND FIELD OPERATIONS

SIZE OF IDENTICAL PARCELS: 302.00 ACRES
 NUMBER OF PARCELS: 120
 LENGTH OF GEOGRAPHIC AREA INCLUDING PLANTATION: 13.95 MILES
 WIDTH OF GEOGRAPHIC AREA INCLUDING PLANTATION: 7.75 MILES
 TOTAL AREA OF PLANTATION: 36000.00 ACRES
 GEOGRAPHIC AREA INCLUDING PLANTATION: 59192.00 ACRES
 PLANTATION DENSITY: 8.52
 TOTAL DISTANCE BETWEEN PARCELS: 0.55 MILES
 AVERAGE TRAVEL DISTANCE FROM PARCEL TO CENTER OF PLANTATION: 5.42 MILES
 LAND COST: 425. \$/ACRE

HYBRID POPLAR NE 388-A

ENTRY	A	N1	N2	M	SURV	YIELD1	YIELD2	PCYDU	ASY
1	4.	2.	2.	5.	10162.	5.5755E-01	3.9154E 00	12.	8.5253E 00

PLANTATION MANAGEMENT

PLANTING UNIT: 3000.00 ACRES
 PLANTS PER ACRE NEEDED TO REPLANT ONE ACRE: 1089.00
 TOTAL PLANTATION ANNUAL YIELD: 317937.88
 TOTAL PLANTATION ANNUAL ENERGY YIELD: 5.4605E 12

FIELD OPERATION	NUMBER	AREA	HOURS	TRAVEL TIME	NUMBER OF TRIPS	NUMBER OF UNITS	YEARLY TOTAL HOURS	TOTAL MAN-YEARS
HARVESTING			32787.34	6.62		5.20	8280.00	207.00
COLLECTION, TRANSPORTATION, AND SPREADING						2.00	3280.00	40.30
						2.00	6020.00	6.66
CULTIVATION		28500.00	6477.27	5.24		3.00	5760.00	8.43
FUNGICIDE APPLICATION		4520.00	1125.00			1.00	1250.00	0.61
LAND CLEARING ROAD MAINTENANCE			3157.89			0.40	3760.00	1.71
REPLANTING	32670000.0		4063.75			2.00	2160.00	0.45
CLOPP MATERIAL PRODUCTION	363000.00			1.31	2.00	1.00	2160.00	1.25

- the number of pieces of equipment required. This estimate takes into account the number of hours required for operations and travel, adjusted for the applicable load factor, the number of hours available yearly to perform the operation and the time required for maintenance and repair. The number so determined is generally rounded to the next higher integer.
- the number of yearly hours of operation per piece of equipment,
- the total number of man-years of operators required by the operation.

The data required are supplied by the various subroutines described before and, in particular, by Subroutine 6.

The product of this part of the field operation subroutine is a printout listing the above-mentioned quantities for each field operation considered (see Figure III-13).

A few comments are made below concerning the various field operations:

-Harvesting-

As indicated in Subroutine 6, a four-row harvester similar to forage corn harvesting machines but reinforced to accomodate juvenile trees has been assumed to exist.

The procedure referred to above to estimate the inventory and manpower requirements for the field operations is illustrated below for the case of harvesting.

The following steps are involved:

$$\begin{aligned}
 (\text{YHH}) &= \text{yearly harvesting hours} \\
 &= (\text{TPAY}) [1 + (\text{MC}/100)](\text{HCA}) \quad (\text{hours/year}) \quad (\text{III-17})
 \end{aligned}$$

where

- (TPAY) = total plantation annual yield (o.d. T/year)
- (MC) = moisture content (percent of o.d. weight)
- (HCA) = harvester capacity (green tons harvested per hour)

(YHTT) = yearly harvester travel time (hours/year)

$$= \frac{(M + 1) N (TDP)}{(n_1 + Mn_2) (HVE)} \quad (III-18)$$

where (TDP) = average travel distance per parcel (miles)

(See Subroutine 1)

(HVE) = harvester velocity (miles/hour)

(NH) = number of harvesters required

$$= \frac{(YHH) + (YHTT)}{[1 - (FMRH)] (NHDY) (NHHD) (LFH)} \quad (III-19)$$

where (FMRH) = fraction of time available for harvesting required for maintenance and repair. When replacement equipment is available, this number is set equal to zero,

(NHDY) = number of harvesting days per year. Site-specific data take into account local climatic conditions (snow, heavy rain) and other restrictions on harvesting period (no harvesting in mid-summer)(days/year). Typical harvesting periods range from about 220 to about 320 days/year.

(NHHD) = number of harvesting hours per day (hours/day)

(HVE) = harvester velocity when moving from parcel to parcel (miles/hour)

(LFH) = load factor of the harvester. This factor (< 1) takes into account time losses in the field for small maintenance, changes of crew, refueling, etc.

The value of (NH) determined through (III-19) is rounded up to the next integer

(YOHH) = yearly operating hours per harvester (hours/year)

$$= \frac{(YHH) + (YHTT)}{(NH) (LFH)} \quad (III-20)$$

(TMYH) = total man-years required for harvesting (m-y/y)

$$= \frac{(NH) (MYHS) (YOH)}{[1-(FMRH)] (2050)} \quad (III-21)$$

where (MYHS) = man-years per full harvester shift.

Typical results are shown in Figure III-13. The example was worked for the following numerical values: (HCA) = 16 green tons/hour, (HVE) = 5 miles/hour, (FMRH) = 0, (NHDY) = 345, (NHHD) = 24, (LFH) = 0.9 (MYHS) = 1.

Fractional numbers of man-years are assumed to represent temporary personnel hired on an as-needed basis. The data printed on Figure III-13 is the basis for the biomass cost subroutine.

- Collection and Transportation of Biomaterial and Spreading of the Recycled Materials

Three alternatives can be selected for the method of transportation of the biomaterial from the point of generation (field) to the point of use (power plant).

TRAN: 1 - This method involves tractor-trailer units following the harvester chipper in the field and collecting the chips. The tractor trailers then deliver the material at the point of use. This method avoids local (field) storage and a supplementary loading step but requires a large investment as expensive hauling units spend a significant amount of time in the fields being loaded by slow-operating harvesters. Also, the period of use of the hauling units is restricted to the period during which harvesting can be performed.

TRAN: 2.- In this method, tractor dumpwagons or small hauling units follow the harvesters in the field and deliver the biomass at a number of storage points located by main roads leading to the point of use. From the storage areas, tractor trailers are loaded and deliver the material to the power plant. Since investment in large hauling vehicles is reduced, delivery can be performed on a more regular basis because the only limitation is road conditions rather than field operations (as in case TRAN: 1), but an extra loading step is necessary at the storage point.

TRAN: 3 - The transportation of the biomaterial from the field to the storage areas is similar to TRAN: 2, i.e. it uses small hauling vehicles and delivery to the point of use is accomplished by pneumatic tubes (39). The tube system requires a high investment but can be operated year-long and reduces the logistical problems associated with over-the-road transportation in the vicinity of built-up areas.

In all cases, recycled materials are returned to and spread on the fields by whichever hauling vehicle is used in the harvesting process. It is thus assumed that some of the hauling units are equipped with spreaders as used in agriculture. The cost of modifying existing units to that effect is included in the quotations of Subroutine 6.

The case analyzed in Figure III-13 corresponds to TRAN: 2 and quotes the inventory and manpower required for both large and small hauling units: the top line of item collection lists the number of small hauling units per harvester, while the second line lists the total number of large hauling units required for over-the-road transportation.

- Cultivation-

Each year, $(M + 1)$ (PU) (acres) are harvested. Depending on the period during

which each planting unit was harvested, the intensity of cultivation during the growing season will vary. Areas harvested from August of the previous year to March of the year considered will regrow fast as the growing season starts and will require the fewest number of cultivations for the season. This number of cultivations for these planting units is C_1 , which will probably be equal to 1. The planting unit which was destroyed and replanted (which will be one of the planting units harvested from August to March) will require the most cultivations-- C_4 cultivations, which is probably equal to 3 or even higher. Similarly, areas harvested during April-May (if harvesting can be done during this early growth period) and June-July will require C_2 and C_3 cultivations, respectively. The values of C_1 to C_4 depend on soil, species, climate, and are considered as site-specific input (see Subroutine 1).

The total area to cultivate during the growing season (TACUL) is estimated with the following equation:

$$(TACUL) = (PU) \left[\left(\frac{M+1}{12} \right) [8 C_1 + 2 (C_2 + C_3)] + (C_4 - C_1) \right] (\text{acres}) \quad (III-22)$$

From (III-22), the inventory of equipment--disks and tractors--and manpower is estimated following the pattern described above for harvesting. Provisions are made in the program for taking into account uses of the tractors other than cultivation (fungicide spraying, for instance) during the growing season when estimating the number of tractors required in the plantation.

The first printout (see Figure III-13) lists the acreage to be cultivated per year as well as the equipment and manpower data.

-Fungicide Spraying-

It is assumed that the areas harvested during the hot and eventually humid part of the growing season will require application of fungicides. The procedure for determining the equipment and manpower required is similar to that for cultivation. See Figure III-13 for the printout.

-Land Clearing and Road Work-

Each year one planting unit is destroyed, i.e., roots removed. This operation as well as road and fire-breaks maintenance is performed by crawlers. The estimates of manpower and equipment needed follow the same pattern as for cultivation. The printout (see Figure III-13) shows only a part-time need for the equipment. In such a case, equipment may be leased or the work subcontracted.

-Replanting-

Each year one planting unit (PU) is replanted. The total number of clones to be replanted per year (TNCRY) is

$$(TNCRY) = 43,560 (PU)/A \quad (III-23)$$

From this number the needs in equipment and manpower (tractor drivers plus replanters) can be estimated (see Figure III-13).

-Clone Material Production-

Each year, a part of the planting unit harvested for the first time (first growth) is reserved to produce the clones needed to replant one planting unit. Dumpwagons and tractors are used to transport the material from the field to the nursery. The equipment listed in Figure III-13 refers to dumpwagons, the tractors being supplied by other teams within the plantation.

c. Nursery Operations

This operation is not a nursery in the usual sense. Rather than growing seedlings, the operation is responsible for producing the clones needed for replanting from the material harvested from a planting unit at the end of its first growth period. The steps involved include: cutting clones from the harvested material, packaging and storing the clones in underground (cinder block, for instance) structures for weeks or months. The necessary equipment involves a building (work area), small tools, packaging and storage space. These, as well as the necessary manpower, are estimated on the basis of the number of clones required. The size of the nursery

operation is thus species-dependent, not only because of the species' specific growth cycle adopted, but also because the optimum dimensions of individual clones are species-specific. For instance, while clones 5 inches long and 1/2-inch in diameter are generally recommended for hybrid poplars (40), clones 18 inches long and 3/4- to 1 inch in diameter are recommended for sycamores (37). Such differences have a large impact on the amount of clone material and storage space required.

d. Supervision

The supervision team includes:

- a plantation manager
- a field foreman for each operating shift in the field
- a motor pool foreman
- a number of clerks-dispatchers
- a horticulturist.

The supervision team has office space, communication equipment and pick-up trucks available. The level of manpower and equipment required is determined on the basis of the size of the plantation. For instance, a half-time horticulturist (consultant for instance) is considered sufficient for plantations up to about 20,000 acres.

Figure III-14 shows the printout for the manpower (expressed in man-years) for the plantation. The pick-up trucks' operating characteristics are included in the motor pool operations.

e. Motor Pool Operations

The major function of the motor pool is to perform the maintenance and repair for the plantation operation. Its second function is to maintain enough equipment on reserve to ensure full-time operation if this approach to plantation management is chosen. As indicated before, the latter mode of operation is adopted when $(FMRX) = 0$, i.e., when "the fraction of time for maintenance and repair of machine X" is set equal to zero.

FIGURE III- 14

PART OF THE COMPUTER PRINTOUT DESCRIBING THE SUPERVISION AND MOTORPOOL OPERATIONS
AND THE PLANTATION INSTALLATION AND START-UP

SUPERVISION	PLANTATION MANAGER	FOREMAN	MOTOR POOL	CLERKS	HORTI
MAN-YEARS	1.00	4.00	1.00	5.00	0.50

MOTOR POOL

TYPE	MAINTENANCE AND REPAIR	RESERVE UNITS	TIME FOR SPRAYING	
HARVESTERS	8.33	2.00		
SMALL HAULING UNITS	4.04	1.00		
HAULING UNITS	0.00	1.00		
CULTIVATORS	0.84	0.00		
FUNGICIDE SPRAYERS	0.00	0.00		
CRAWLERS	0.53	0.00		
REPLANTERS	0.53	0.00		
DUMP WAGONS	0.11	0.00		
TRACTORS	1.54	0.00	15546.76	3.00
PICKUP TRUCKS	2.31	0.00		

YEARLY OPERATING HOURS PER TRACTOR: 8336.67
 TOTAL MAN-YEARS FOR TRACTOR OPERATORS: 12.20
 YEARLY OPERATING HOURS PER PICKUP TRUCK: 2370.31
 MOTOR POOL BUILDING AREA (SQUARE FEET): 25000.00

PLANTATION INSTALLATION

TOTAL AREA TO CLEAR: 36000.00
 TOTAL AREA TO PREPARE: 100000.00
 TOTAL AREA TO FERTILIZE: 66000.00
 AMOUNT OF FERTILIZER TO SPREAD: 8735.15 TONS
 AMOUNT OF LIME TO SPREAD: 33000.00 TONS

POSITION MAN-YEARS

PLANTATION MANAGER	2.00
FOREMAN	2.00
MOTOR POOL FOREMAN	0.50
CLERKS	4.00
HORTICULTURIST	1.00

PLANTATION START-UP

NUMBER OF CLONES TO

BUY	PLANT	PRODUCE
16312501.00	391500000.00	375187488.00

TOTAL ACREAGE TO BE CULTIVATED DURING START-UP: 138000.00
 AMOUNT OF MATERIAL TO BE HARVESTED DURING START-UP: 127482.11

The manpower required for maintenance and repair of the various types of the equipment is estimated through

$$\begin{aligned}
 (\text{TMYMRX}) &= \text{total man-years for maintenance and repair of equipment} \\
 &\quad \text{X (man-year/year)} \\
 &= \frac{(\text{NX}) (\text{YOHX}) (\text{FDTX}) (\text{MYMRX})}{2,050} \quad (\text{III-24})
 \end{aligned}$$

where (NX) = number of units of type X

(YOHX) = yearly operating hours of X

(FDTX) = fraction of downtime of X for maintenance and repair (numerically equal to (FMRX) when this quantity is not zero)

(MYMRX) = number of workman required to repair X. For small equipment (truck, tractor, etc.), this number is generally 1. For large units, more than one mechanic may be necessary at any time.

The number of units of type X in reserve where this mode of operation is used is given by

$$\begin{aligned}
 (\text{NXR}) &= \text{number of units X in reserve} \\
 &= (\text{NX}) (\text{FDTX}) \quad (\text{III-25})
 \end{aligned}$$

These numbers are rounded to the next integer. Figure III-14 shows the printout for the motor pool operation. The first column (Maintenance and Repair) states the man-years of mechanics required to maintain the equipment while the second column states the number of units of each type in reserve. The tractors appear as a separate item as these units are used for several operations (cultivation, fungicide, nursery) and require a separate accounting to avoid duplication and permit the simultaneous performance of several operations.

f. Plantation Installation

The plantation installation operations include clearing of the land (removal of natural stands, brush, etc.) , cultivation (plowing, disking),fertilization, and lime-spreading. These operations extend over a period of $(n_1 + n_2)$ years so that, after that period, the plantation is capable of operating at full capacity according to the management schedule described in Section (7)a. The quantities of fertilizer and lime are determined in the same way as for the operating plantation, but no recycling of materials from the ponds or power plants is assumed. Similarly, no credit is taken for biomaterial harvested while clearing the land; the wood chips are assumed to be returned to the land as a soil conditioner. During the installation period, the supervisory and other teams are progressively assembled and the equipment purchased.

All plantation installation operations are assumed to be subcontracted to local operators. The printout lists the items required to estimate the installation costs: acreage to clear, acreage to cultivate, fertilizer, etc. (see Figure III-14).

g. Plantation Start-up

The start-up operations include the planting of seedlings and clones, cultivation for weed control, partial harvesting and production of clones. The initial planting, covering only a fraction of the plantation area, is made from purchased seedlings. Most of these start-up operations are also subcontracted to local operators while the equipment and work force of the plantation are brought together.

Figure III-14 lists the items required to estimate the start-up costs: number of seedlings to purchase, number of clones to produce, area to cultivate, etc.

Two elements are crucial in the successful establishment of a plantation: soil moisture and cultivation to avoid competition from weeds and other parasitic vegetation (52 to 55). Cultivation (disking) is included as a standard operation in plantation management (see cultivation in section b. Field Operations). In the planning of plantation operations, planting is assumed to take place in late winter or early spring when the climatic conditions permit access to the fields and when soil moisture exceeds evapotranspiration as recommended in reference 55. With these precautions --moisture and cultivation--and good quality planting stock--seedlings or clones--survival at year one reaches the percentage levels mentioned earlier in the text (55, 57).

h. Uncertainties

The major uncertainties in this subroutine are related to the uncertainties or limitations of the plant-growth model (number of successive harvests, yield-cycle combinations, etc), the uncertainties concerning harvesting at certain periods of the year, and the uncertainties concerning the harvesting equipment. Other operations are similar to or extensions of known agricultural techniques and are thus well established.

(8) Data Base for Cost Estimates

This subroutine is a data bank containing the costs of supplies, fertilizer, fuels, etc. needed in Subroutine 9. These items are site-specific. Values quoted for farm products in March 1977 (41) for various regions of the U.S. are used in this data bank. Financial information needed to estimate the cost of biomass according to the two methods of financing considered are also quoted: interest rates on debt and equity, fractions of debt and equity, etc.

(9) Cost-of-Biomass Subroutine

The cost of biomass is estimated on the basis of the utility and municipal methods of financing (see Appendix A). The steps involved in this subroutine are:

1. estimate of the investment and yearly depreciations for the machinery and buildings of the plantation (see typical printout on Figure III-15). The investments are calculated on the basis of the inventories determined in Subroutine 7 and the unitary costs listed in the data base of Subroutine 6. The yearly depreciations are calculated on the basis of the yearly operating hours and the depreciation periods listed in Subroutines 6 and 8, respectively.
2. estimate of yearly amounts and costs of supplies. The major items--nutrients--are estimated on the basis of the equations given in Subroutine 3 and the base costs given in Subroutine 8. Figure III-15 shows a typical printout for the yearly supplies.
3. estimate of the yearly operating costs. Two sets of values corresponding to the two methods of financing are given. The differences between the two methods are due to the differences in land rental costs and in local tax and insurance, as is apparent in the printout of Figure III-15.

FIGURE III-15

PART OF THE COMPUTER PRINTOUT DESCRIBING THE FINANCIAL PART OF THE
PROGRAM

FINANCIAL

TYPE	INVESTMENT	DEPR./YR
HARVESTERS	721000.00	243668.56
SMALL HAULING UNITS	176000.00	88320.00
HAULING UNITS	228000.00	59323.32
TUBE SYSTEM	0.00	0.00
CULTIVATORS	6600.00	4339.73
FUNGICIDE SPRAYERS	2900.00	413.81
CRAWLERS	14619.80	6423.51
REPLANTERS	4200.00	648.00
DUMP WAGONS	2600.00	460.00
TRACTORS	52800.00	18864.69
PICKUP TRUCKS	24000.00	3250.71
NURSERY BUILDING	15524.78	776.24
MOTOR POOL BUILDING	180000.00	5000.00

YEARLY SUPPLIES

TYPE	AMOUNT	COST
NITROGEN	3438.22	1364972.00
PHOSPHORUS	130.89	42935.45
POTASSIUM	2028.44	361062.97
LIME	928.06	2882.90
FUNGICIDE		45000.00
SMALL TOOLS		20000.00
NURSERY		6209.91
MOTOR POOL		10000.00
TOTAL YEARLY SUPPLIES COST		1859038.37

YEARLY OPERATING COSTS

ITEM	AMOUNT	COST (UTILITY)	COST (MUNICIPAL)
GASOLINE	23703.13	12799.69	12799.69
DIESEL	303047.97	127282.14	127282.14
LAND RENTAL		1930050.00	1113075.00
OPERATING LABOR		656330.44	656330.44
MAINTENANCE LABOR		201104.00	201104.00
SUPERVISION		116500.00	116500.00
ADMINISTRATION AND OVERHEAD		194450.00	194450.00
PLANTATION SUPPLIES		1859038.37	1859038.37
MAINTENANCE AND REPAIR		322617.00	322617.00
LOCAL TAXES AND INSURANCE		82100.00	39500.00
TUBE SYSTEM		0.00	0.00
TOTAL		5508650.00	4641000.00

4. estimate of depreciable and nondepreciable investments, yearly depreciation and annual equivalents. These operations are performed following the format described in Appendix A using the quantities calculated in 1. to 3. above. Figure III-16 shows a printout of this last step which leads to an estimate of the cost of biomass on an oven-dry basis, green-wood basis and Btu content for both the utility and the municipal methods of financing.

(10) Assumptions and Limitations of the Energy Plantation Model

1. The Energy Plantation model does not include irrigation of the plantation. It is thus only applicable for areas of the United States where sufficient rainfall (20-25 inches) is available during the growing season to sustain yields of deciduous trees of 5 to 10 o.d. tons/acre-year.
2. Fertilizer is assumed to be applied to the plantation in the amounts required to replenish the nitrogen, potassium, phosphorus and calcium removed through repeated, short-rotation harvests. Optimization of fertilization for maximum economic return from the land is not included in the model.
3. Annual sustained yields are estimated from the plant growth-harvesting cycle subroutine. This subroutine reproduces experimental data within 5 to 10 percent for the sites at which the data base was generated (see Appendix C). Estimates for sites at which no experimental data exist are obtained through the use of a weighting factor measuring the relative productivities of the site considered and the site at which the data base was generated. Yields predicted on this basis are estimated to be valid within ± 20 percent of the values quoted.
4. It is assumed that five coppice harvests can be obtained from a deciduous hardwood plantation with no change in annual sustained yields.
5. It is assumed that a harvester-chipper is available. While the characteristics of this hypothetical machine (chipping rate, fuel consumption) are similar to those of existing whole-tree chippers, there is considerable uncertainty as to the price of such a machine when commercially available.
6. It is assumed that the plantation is made up of individual parcels having an area equal to the average size of farms in the region of interest. This may be too restrictive as fairly large blocks of unused or underused land might be available for plantation applications.

7. It is assumed that the ratio of the land used for plantation purposes to the geographic area within which it is contained is equal to the ratio of the acreage of land in classes 4 to 6 (marginal farmland) to the total acreage of farmland in the area. This distribution or plantation density may have an important impact on the economics of biomass production.

The impact of assumptions 3. to 7. on the economics of the plantation is discussed in the sensitivity analysis performed for a site in Louisiana (see section 3b below).

3. Analysis of the Natchitoches, Louisiana, Site

The Natchitoches, Louisiana, site was used as a test case for the plantation computer model. The input data are shown in Table III-15. Table III-16 shows the list of species selected with the corresponding yield-cycle combinations. Because of the uncertainty on the eastern cottonwood data at high planting densities, a bracket of values (high and low) is given for the yields. The program estimates the cost of biomass for these (and any other added) yield-cycle combinations. In accordance with the general principle that several species will be grown at each site, the cost of biomass quoted for any given site is an average of the values obtained for the various species-yield-cycle combinations at the site. The forthcoming analysis of the Natchitoches, Louisiana, site, however, is based on the computer analysis for one species-yield-cycle combination, i.e., hybrid poplar NE388- $4 \text{ ft}^2/\text{tree-n}_1 = 2\text{-n}_2=2$. This approach is adopted to separate the effects of species and cycles from other parameters on the cost of biomass.

a. Components of the Cost of Biomass and Efficiency

The printouts presented in Figures III-13 to 16 correspond to the test case considered here for a 36,000-acre plantation.

Table III-17 shows the major contributors to the cost of biomass (see Appendix A and Figures III-15 and 16). In both the utility and the municipal methods of financing, the major contributor to the cost of biomass is the annual operating cost (70 to 80 percent). Table III-18 shows the breakdown of the yearly

FIGURE III-16

PART OF COMPUTER PRINTOUT DESCRIBING ESTIMATE OF COST OF BIOMASS

INVESTMENT	Utility	Municipal
TOTAL MACHINERY AND BUILDINGS:	1172344.75	1172344.75
PLANTATION INSTALLATION:	1878786.37	1878786.37
MACHINE AND LAND PREPARATION:	3342951.25	3342951.25
START-UP:	1528383.52	1528383.52
INTEREST DURING CONSTRUCTION ON MACHINERY AND BUILDINGS:	65859.59	37365.38
INTEREST DURING CONSTRUCTION ON LAND CLEARING AND PREPARATION:	415296.81	238515.86
DEPRECIABLE INVESTMENT:		
WORKING CAPITAL:	918189.19	773511.63
NON-DEPRECIABLE INVESTMENT:		
TOTAL INVESTMENT:	5961728.58	5612647.88

YEARLY DEPRECIATION	UTILITY	MUNICIPAL
MACHINERY AND BUILDINGS:	343156.56	343156.56
PLANTATION INSTALLATION:	56121.19	56121.19
START-UP:	45689.11	45689.11
IDC FOR MACHINERY AND BUILDINGS:	3983.57	2241.92
IDC FOR LAND CLEARING:	12458.98	7155.45
TOTAL DEPRECIATION:	461249.31	454284.19

ANNUAL EQUIVALENTS	UTILITY	MUNICIPAL
DEPRECIABLE INVESTMENT:	1634489.75	938727.19
NON-DEPRECIABLE INVESTMENT:	181918.12	49311.36
DEPRECIATION:	461249.31	454284.19
GROSS RETURN:	1275152.50	533754.37
RETURN ON EQUITY:	361867.83	8.88
FEDERAL INCOME TAX:	334831.89	8.88
TOTAL REVENUE REQUIRED FOR YEAR:	7579886.88	5629128.88

	UTILITY	MUNICIPAL
PRODUCT COST:	23.84	17.71
PRODUCT COST AS DELIVERED (GREEN CHIPS):	14.45	10.73
ENERGY COST:	1.39	1.83

TABLE III-15

INPUT DATA FOR THE NATCHITOCHES, LOUISIANA, SITE

Parcel size:	PAR: 250 (acres)
Forest group:	FOG: 5 b
Land class:	CLA: 4
Land cost:	LACOST: 485 (\$/acre)
Growing season:	DGS: 240 (days)
Cultivation frequency:	
	C ₁ : 1
	C ₂ : 2
	C ₃ : 1.5
	C ₄ : 3
Nitrogen from sludge:	(NSLU): 59.1 (T/year)
Phosphorus from sludge:	(PSLU): 7.4 (T/year)
Weighted land class:	(AWLC): 0.80
L _g /W _g :	1.8
Plantation density:	0.52

TABLE III-16

SPECIES SELECTED AND YIELD-CYCLE COMBINATIONS FOR THE
NATCHITOCHES, LOUISIANA, SITE

(Number of coppice harvests: M=5)

Species	<u>A.</u> <u>ft²/tree</u>	<u>n₁</u> <u>year</u>	<u>n₂</u> <u>year</u>	<u>Average Sustained Yield</u> <u>o.d. T/acre-year</u>
Hybrid Poplar NE 388	4	2	2	8.53
	6	2	2	8.27
	8	2	3	8.18
Hybrid Poplar 252	4	2	2	10.00
	6	2	2	9.09
	4	3	2	9.08
Silver Maple	4	2	3	5.20
Missouri Cottonwood	4	2	2	7.50
	6	2	3	7.34
Eastern Cottonwood				
High	4	2	3	10.86
Low	4	2	3	4.29
Sioux Male Cottonwood	4	2	2	10.74
	6	2	2	10.33
Sycamore	4	2	4	7.11
	4	2	5	6.86

TABLE III-17

SUMMARY OF THE FINANCIAL DATA FOR THE NATCHITOCHES, LOUISIANA, SITE
 (36,000-acres plantation, hybrid poplar NE 388-4-2-2, 8.52 o.d T/acre-year)

Annual Equivalent	Utility		Municipal	
	\$	%	\$	%
Depreciable Investment	1,634,489	22	938,727	17
Non-depreciable Investment	101,910	1	49,311	1
Federal Income Tax	334,031	4	0	0
Annual Operating Costs	5,508,655	73	4,641,069	82
Total Revenue Required	7,574,085	100	5,629,108	100
Product Cost (\$/o.d.T)	23.84	-	17.71	-
(\$/10 ⁶ Btu)	1.39	-	1.03	-

operating costs for the case considered. For utility financing, land rental, nutrients (mostly nitrogen) and labor are the major contributors to operating costs, amounting to about 85 percent of the total. For municipal financing, nutrients, land rental and labor amount to about 83 percent of the total operating costs. The possibility of reducing the contribution of those items will be discussed in subsequent sections.

The second major item in the cost of biomass is the annual equivalent of the depreciable investment. The major components of the investment are: machinery and buildings (19.7 percent) , plantation installation (31.4 percent) and plantation start-up (25.5 percent). In the case considered, the total investment amounts to about six million dollars, or \$18.75 per oven-dry ton delivered and \$17.65 per o.d.T delivered for the utility and municipal financing methods, respectively.

The energy efficiency of the plantation considered was estimated through:

$$\eta = \frac{E_{out} - E_{in}}{E_{out}} \quad (III-26)$$

where E_{out} = yearly energy output from the plantation (Btu/y)
 E_{in} = yearly energy input from fuels and ammonium nitrate fertilizer. Only nitrogen fertilizer was considered as it accounts for most of the supplies' energy input.

Using data for large-scale production of ammonium nitrate from natural gas (42), the efficiency of the plantation considered here is about 97 percent; i.e., only the equivalent of 3 percent of the energy produced is required to operate the plantation (see Appendix C for details).

The data discussed above will be influenced by a number of factors, some of which are examined below.

TABLE III-18

BREAKDOWN OF OPERATING COSTS FOR THE NATCHITOCHES, LOUISIANA, SITE

(36,000 acres-hybrid poplar NE 388-4-2-28.52 oven-dry ton/acre-year)

<u>Items</u>	Utility		Municipal	
	\$	%	\$	%
Fuels	140,080	2.5	140,080	3.0
Land Rental	1,938,060	35.2	1,113,075	24.0
Operating Labor	654,595	(11.9)	654,595	(14.1)
Maintenance Labor	201,155	(3.7)	201,155	(4.3)
Supervision	116,500	(2.1)	116,500	(2.5)
Total Labor	972,250	17.7	972,250	20.9
Administrative and Overhead	194,450	3.5	194,450	4.2
Supplies - Nitrogen	1,364,972	(24.8)	1,364,972	(29.4)
Phosphorus	42,930	(0.8)	42,930	(0.9)
Potassium	361,063	(6.5)	361,063	(7.8)
Lime	8,863	(0.1)	8,863	(0.2)
Total Nutrients	1,777,828	32.2	1,777,828	38.3
Others	81,210	1.5	81,210	1.7
Maintenance and Repair	322,618	5.9	322,618	7.0
Local Taxes and Insurance	82,160	1.5	39,558	0.9
Irrigation System	0	-	0	0
Total	5,508,656	100	4,641,069	100

b. Sensitivity Analysis

The influence of various factors on the cost of biomass is examined for the case of the Natchitoches, Louisiana, site. The analysis is restricted to one species-yield-cycle combination, but the results are generally valid for any combination.

-Plantation Size

Figure III-17 shows the dependence of the cost of biomass on plantation size for the three transportation methods considered (see Section(7)). The fluctuations of cost around the generally decreasing function correspond to the degree of matching of the equipment with the amount of biomass generated.

It is apparent that transportation method TRAN 1 (large hauling units following the harvester) is the least favorable. Above about 40,000 acres, pneumatic tube systems are the most economical and the associated cost of biomass remains essentially constant. For medium-sized plantations, 10,000 to 40,000 acres, transportation methods 2 or 3 (small and large hauling units or pneumatic tubes) are essentially equivalent. For the conditions of the example, the most economical plantation size is between 30,000 and 40,000 acres and over. Similar results were found for other cases.

-Size of the Parcels

As noted earlier, in the absence of a better description, the plantation is assumed to be made of a number of identical parcels. Preliminary data indicate that, for plantations of the order of 20,000 acres and high plantation density (ratio of plantation to geographic areas), the size of the parcels influences very little the cost of biomass down to parcels of the order of 100 acres. Below this value, an increase in cost of about 30 percent was estimated as the size of the parcels decreased to about 50 acres.

FIGURE III-17

INFLUENCE OF PLANTATION SIZE ON THE COST OF BIOMASS

(Municipal Financing - Natchitoches, LA, Site)

-Plantation Density

The plantation density measures the distribution of the plantation area within the geographic area considered. For plantations made of large parcels, the plantation density does not seem to affect the cost significantly. The situation could however be quite different for small parcels involving significant transit time of equipment from parcel to parcel.

-Biomass Transportation

This topic is addressed above (see 3.b., influence of plantation size).

-Species Selection and Yields

All other things being equal (cycle, etc.), a change of species in the plantation will generally result in a change of yield (o.d. ton/acre-year). An increase of yield per acre-year is apparently beneficial but will also require more harvesting and transportation equipment. Table III-19 compares the investment and material costs for two varieties of hybrid poplar and Sioux male cottonwood, all grown according to the same cycle, i.e. 4-2-2.

Improving the yields through the choice of different species generally decreases the cost of biomaterial, but this effect is offset in some cases by secondary effects. For instance, the clone material and production costs for cottonwood is higher than for poplars; moisture content of cottonwood is higher than for poplar, resulting in higher transportation costs for green cottonwood chip. Thus, the effect of changes in species is species-specific. Increasing yields through species changes also generally increases the investment per unit biomass produced per year. The efficiency of the plantation is apparently unchanged; i.e., the increase in amounts of fuel per operation is offset by the increase in harvest.

Comparing the results for hybrid poplars, it appears that a reduction of yield of about 15 percent leads to an increase in fuel cost of about 9.6 percent. Similar values of ratio of changes are obtained for other cases, which suggests that variations of one percent in yield result

TABLE III-19

COMPARISON OF BIOMASS COST FOR VARIOUS SPECIES GROWN AT THE MATCHITOCHES, LOUISIANA, SITE
 (36,000 acres - 4 ft²/tree - 2 years interval between harvests - municipal financing)

	Yield	Cost		Investment	Production	Efficiency
	<u>o.d. T/a-y</u>	<u>\$/o.d. T</u>	<u>\$/10⁶ Btu</u>	<u>\$/o.d. T-year</u>	<u>O.d. T/y</u>	<u>%</u>
Hybrid Poplar NE 388	8.52	17.71	1.03	17.65	317,938	96.95
Hybrid Poplar 252	10.00	16.18	0.94	19.99	366,582	97.35
Sioux Male Cottonwood	10.74	17.66	1.03	18.71	397,859	96.86

in variations of 0.5 to 0.6 percent in biomaterial cost. This conclusion suggests that even significant variations in yields due to seasonal fluctuations or systematic error in the plant-growth model will not affect too drastically the predictions of the plantation model.

-Yield Cycle Combinations

Changes in yield-cycle combinations for a given species result in complex effects, such as change in yield, harvesting schedule, and planting requirements.

Table III-20 compares two such cases. In the case of hybrid poplar, a change in deviation of first growth results in a decrease in yield by 7 percent. This results in an increase in cost of 5 percent, increase in unitary investment of 13 percent and no change in efficiency. In the case of Missouri cottonwood, a change of planting density and harvesting cycle results in a decrease in yield of 2 percent accompanied by a decrease in cost of one percent and a small increase in efficiency. Thus, the slight reduction in yield is compensated by a larger reduction in planting and harvesting operations, leading to a lower price. This case illustrates the flexibility of the model: optimization for highest amount of biomaterial suggests the 4-2-2 cycle at slightly higher cost while optimization for lowest cost suggests the 6-2-3 cycle at somewhat lower productivity. The above examples thus show that changes in yield-cycle combinations may have a more direct effect than changes in yields only.

-Change in the Number of Coppice Harvests

Although indications are that up to five coppice harvests can be obtained from one planting (40), not enough experimental data are available to confirm this. Reducing the number of coppice harvests M from 5 to 3 increases the cost of biomass by almost 9 percent, while increasing M above 5 reduces the cost of biomass by about 2 percent per unit value of M . The dependence of the cost on M is thus significant and warrants further investigation.

TABLE III-20

EFFECT OF CHANGES IN YIELD-CYCLE COMBINATIONS ON THE COST OF BIOMASS FOR THE NATCHITOCHES,LOUISIANA, SITE

(36,000 acres - municipal financing)

	Cycle	Yield	Cost		Investment	Production	Efficiency
	<u>-</u>	<u>o.d. T/a-y</u>	<u>\$/o.d T</u>	<u>\$/10⁶ Btu</u>	<u>\$/o.d. T-year</u>	<u>o.d. T/y</u>	<u>%</u>
Hybrid Poplar 49	4-2-2	8.96	17.17	1.00	17.46	334,435	97.65
	4-3-2	8.33	18.06	1.05	20.13	308,290	96.92
Missouri Cottonwood	4-2-2	7.50	19.75	1.15	22.14	278,060	96.83
	6-2-3	7.34	19.53	1.14	22.38	273,014	97.77

-Influence of the Value of Land

As expected from the discussion in 3a., the cost of biomass is very sensitive to the cost of land. For prices of land in the range of \$500/acre, an increase of land cost of one percent translates to an increase in cost of biomass of about 2.5 percent.

-Influence of the Cost of the Harvester

At present there is some uncertainty as to the cost and performance of harvesters. It was found that doubling the cost of the harvester would lead to an increase in cost of biomass of 6 to 10 percent. This aspect should be further investigated.

-Influence of the Cost of Fertilizer-

As indicated in section 3a. above, the cost of nutrients, and in particular nitrogen, is a major item in the operating costs. Instead of the value of \$466 per ton of nitrogen, a value of \$300 was assumed. The latter value would correspond to nitrogen supplied by a nitrogen-fixing cover crop (clover, for instance) and includes the cost of seeds, seeding, etc. This reduction in nitrogen cost of about 35 percent leads to a reduction of about 5 percent of the cost of biomass--a fact that should be further explored. An alternative method of reducing the cost of fertilization would be the application of liquid fertilizer throughout the growth cycle rather than once, initially, after harvest. This would decrease the losses and thus the amounts of fertilizer required.

c. Conclusions

The analysis of the Louisiana site shows that:

- high plantation densities and short rotations (4 to 6 ft² per tree and 2 years between harvests) are generally preferred;
- the major component in the cost of biomass is the annual operating cost (among these, land rental, nutrients and labor are the major items);

- for plantations larger than about 20,000 acres, with municipal financing, the cost of biomass is on the order of \$1.20 to 1.30 per million Btu,
- for large plantations (40,000 acres and more), pneumatic tube transportation appears the best method of delivery of the chips (this point should be further investigated);
- except for small parcels (50 acres), the size of the parcels making up the plantation does not seem to have a drastic effect on cost, but should, however, be further investigated for other plantation density values;
- the effect of plantation density should be further investigated;
- changes in sustained yields (o.d. Tons/acre-year) without modifications to the harvest cycle have a relatively small effect on cost;
- changes in yield-cycle combinations and the number of coppice harvests have a strong impact on the cost of biomass, an aspect of the plant-growth model that should be developed since it appears crucial to the economics of the plantation; and
- further investigations should be made to improve: methods of application of fertilizer or replacement of chemical fertilizers (mostly nitrogen) by nitrogen-fixing cover crops.

4. Comparison of the Selected Sites for Plantation Demonstrations

The 15 selected sites have been analyzed on the basis of the plantation model discussed in the preceding sections. In each case, a selection of species with associated cultural cycles and corresponding costs were determined. In each case, average values of productivity and costs are quoted since the plantation is assumed to be made up of a mixture of various species.

Table III-21 summarizes the plantation data for the sites: the area quoted in each case is that area smaller than about 40,000 acres leading to the minimum biomass cost; the cycles quoted are typical cycles for the site ($\text{ft}^2/\text{tree-age at first harvest-duration of coppice growth}$); the list of species retained at each site is not all-inclusive; only species included in the data bank are reported, and the average sustained yields are averages for all the species proposed for the site.

TABLE III-21
CHARACTERISTICS OF THE PLANTATIONS FOR THE SELECTED SITES

<u>Sites</u>	<u>Area (Acres)</u>	<u>Cycles and Species</u> ⁽¹⁾	<u>Sustained Yields</u> ⁽²⁾ o.d.t/a-y
Knoxville, TN	33,000	4-2-2, HP1; 4-2-3, HP2; 4-2-4, SM; 6-2-4, SY	4.41
Natchitoches, LA	36,000	4-2-2; HP1; 4-2-3 HP2; 4-2-4, SM; 6-2-2, MC; 6-2-3, SMC; 6-2-4, EC, SY	7.55
Greenwood, TN	30,000	4-2-2, HP1; 4-2-3 HP2; 6-2-4, SY	6.50
Chanute, KS	36,000	6-2-3, EC	7.45
Martinsville, VA	30,000	4-2-2, HP1; 4-2-3 HP2; 6-2-4 SY	7.06
Maysville, KY	36,000	4-2-2, HP1; 4-2-3 HP2; 4-2-4, SM; 6-2-3, EC; 6-2-4, SY	4.12
Pensacola, FL	24,000	4-2-2, HP1; 4-2-3, HP2; 4-2-4, SM; 6-2-3, EC, SY; 18-2-3 E	8.00
Kissimmee, FL	36,000	4-2-2, HP1; 4-2-3, HP2; 4-2-4, SM; 6-2-3, EC, SY; 18-2-3, E	7.06
Yazoo City, MS	36,000	4-2-2, HP1; 4-2-3, HP2; 4-2-4 SM; 6-2-3, EC; 6-2-4, SY	5.62
Hammond, NY	36,000	4-2-3, HP2; 4-3-3; HP3; 6-2-2 SM	6.37
Bemidji, MN	27,000	4-3-3, HP3; 6-2-3, MC, SMC	9.05
Traverse City, MI	36,000	4-2-3, HP1; 4-3-3, HP3; 6-2-3, SMC	6.32
Caldwell, TX	36,000	6-2-3, EC	7.38
Minden, LA	36,000	4-2-2, HP1; 4-2-3, HP2; 4-2-4, SM; 6-2-3, EC; 6-2-4, SY	7.04
Jamestown, NY	33,000	4-2-2, HP1; 4-3-3 HP3; 6-2-3, EC; 6-2-4, SY	6.59

- (1) HP1 = Hybrid Poplar NE 388, HP2 = Hybrid Poplar NE 252,
 HP3 = Populus Tristis; SM = Silver Maple; MC = Missouri Cottonwood;
 SMC = Sioux Male Cottonwood; EC = Eastern Cottonwood; SY = Sycamore;
 E = Eucalyptus.

Cycle: x-y-z: x ft² per plant at planting, y = age at first
 harvest, z = coppice growth period. The values of x, y and z are those
 which result in the least cost (\$/o.d.ton) of delivered wood chips.

- (2) Average sustained yield for the species selected for each site.

TABLE III-22

COMPARISON OF THE SELECTED SITES

Sites	Annual Production o.d. T/year	Cost \$/o.d.T	Investment \$/o.d. T-y	Efficiency %	Uniformity %
Maysville, KY	152,890	25.95	152.3	2.34	86
Chanute, KS	277,030	20.27	113.3	2.25	92
Martinsville, VA	218,333	19.85	28.3	2.31	75
Caldwell, TX	274,615	22.08	98.7	2.26	87
Bemidji, MN	249,712	17.27	29.9	2.45	75
Traverse City, MI	232,313	23.78	37.9	2.43	80
Hammond, NY	236,781	19.41	31.9	2.42	64
Yazoo City, MS	208,655	20.06	31.3	2.33	96
Kissimmee, FL	261,952	18.83	95.9	2.32	90
Pensacola, FL	197,974	21.27	26.6	2.15	89
Jamestown, NY	224,641	20.57	31.6	2.38	83
Greenwood, SC	201,057	17.53	30.0	2.31	76
Knoxville, TN	150,079	25.79	38.4	1.62	75
Natchitoches, LA	278,437	19.67	26.3	2.29	89
Minden, LA	261,401	18.93	26.3	2.32	84

TABLE III-23

RANKING OF THE SELECTED SITES FOR PLANTATION APPLICATIONS

Sites	Productivity	Annual	Cost	Unitary	Efficiency	Uniformity	Cost	
	<u>o.d. T/a-y</u>	<u>Production</u> <u>o.d. T/y</u>	<u>\$o.d. T</u>	<u>Investment</u> <u>\$/o.d. T-y</u>	<u>%</u>	<u>%</u>	<u>All⁽¹⁾</u>	<u>Invest. Eff.⁽²⁾</u>
Maysville, KY	15	14	15	15	11	9	15	15
Chanute, KS	4	2	9	14	3	14	7	9
Martinsville, VA	6	10	7	4	6	2	4	5
Caldwell, TX	5	3	12	13	4	10	10	12
Bemidji, MN	1	6	1	5	15	2	2	6
Traverse City, MI	12	8	13	10	14	6	13	14
Hammond, NY	11	7	5	9	13	1	7	11
Yazoo City, MS	13	11	8	7	10	15	14	8
Kissimmee, FL	6	4	3	12	8	13	7	7
Pensacola, FL	2	13	11	3	2	11	6	4
Jamestown, NY	9	9	10	8	12	7	11	13
Greenwood, SC	10	12	2	6	6	5	5	3
Knoxville, TN	14	15	14	11	1	2	12	9
Natchitoches, LA	3	1	6	1	5	11	1	1
Minden, LA	8	5	4	1	8	8	3	2

(1) Ranking based on all criteria

(2) Ranking based on cost, unitary investment and efficiency.

In most cases the optimum plantation size is on the order of 30,000 to 36,000 acres. Except for the sites that include eucalyptus as a possible species, the cycles are very similar: 4 to 6 ft² per plant, 2 to 3 years at first harvest and 2 to 4 years for coppice growth. The wide variations in sustained yields are generally related to the quality of the land at the proposed sites.

The sites are then compared on the basis of:

- the total yearly production (o.d. Ton/year)
- cost of biomass (\$/o.d. Ton)
- unitary investment (\$/o.d. Ton-year for municipal financing)
- energy efficiency (see Section 3a)
- uniformity of productivity between species selected (o.d. Tons/acre-year).

The range of sustained yields for the species selected is expressed as percent of the average yield quoted in Table III-21. A wide range around the average suggests uncertainties in the predictions (growth model) or possible fluctuations in yield due to local conditions (soil, climate).

The results are shown in Table III-22.

Table III-23 summarizes the comparison between the sites: for each basis of comparison, the sites are ranked from 1 to 15.

The basis for comparison includes:

- productivity (o.d. Ton/acre-year see Table III-21)
- items included in Table III-22.

A first, overall ranking established on all criteria lists Natchitoches, Louisiana; Bemidji, Minnesota; Minden, Louisiana; and Pensacola, Florida, as the first four preferred sites for an Energy PlantationTM. For the purpose of demonstrating the concept of the Energy PlantationTM, more emphasis should be placed on the cost, the unitary investment and the energy efficiency of the system. On the basis of these three criteria, the

*The number quoted is the percentage fraction of the energy produced required to operate the plantation and produce the nitrogen fertilizer.

two Louisiana sites, Greenwood, South Carolina; and Pensacola, Florida, rank as the first four candidates. That the Louisiana sites and Pensacola, Florida, rank among the first four in both rankings strongly recommends these sites for demonstration purposes.

D. Power Plant Subsystem

1. General Description

A schematic diagram of the components and material flows in the power plant model is shown in Figure III-18. The heavier outer line encloses the total power plant. Interactions between the power plant and other components of the PEF are indicated by flow lines that cross this outer boundary. The fuel is supplied from the Energy PlantationTM. The exhaust gas, heated condenser cooling water, and ash are at least partially supplied to the algae pond system. The dirt can be redistributed onto the Energy PlantationTM land so that its nutrient value is not lost. The electricity, of course, is the primary output of the power plant and is fed into a power grid for use as demanded by the specific site. Combustion air and tempering air are supplied directly from the surrounding atmosphere.

2. Description of System Modeled

The power cycle modeled is a conventional steam Rankine cycle as is used in coal-fired and nuclear power plants. More exotic power cycles such as a gas turbine were not modeled, in keeping with the decision that the model should represent "state-of-the-art" equipment which would be readily available for a demonstration system. The system components are similar to those that would appear in a simple coal-fired power plant with the addition of equipment to dry and screen the fuel before it enters the boiler. Storage space for dried fuel is provided in the event that a continuous supply of fuel from the Energy PlantationTM is interrupted.

Two dryers are shown on the schematic; the first or primary dryer utilizes the flue gas directly as the source of drying energy. A screener is operated in conjunction with this dryer to screen out fine dirt and fuel from the main fuel supply. These screened-out fuel fines are burned in the auxiliary dryer to provide additional drying energy. Tempering air

FIGURE III-18: POWERPLANT SCHEMATIC

can be provided to the primary dryer to prevent combustion from overheating of the fuel in the dryer. The basic model, however, assumes no tempering air flow and uses excess energy in the flue gas to preheat the incoming combustion air, thereby recovering energy which would otherwise be lost in the flue gas.

Removal of particulates from the flue gas is provided for in two locations; namely, in the high-temperature stream between the air preheater and primary dryer, and in the low-temperature exhaust gas stream leaving the dryers.

The term "parasitic power" refers to electrical power that is used within the power plant itself to power the internal equipment.

3. Performance and Cost Model

The steam cycle depicted in the power plant schematic is a simple cycle consisting of the four basic elements of boiler, turbine, condenser and pump. To calculate the energy transfer rates to and from the steam in each of these components, certain relationships between various steam properties must be known. These include, for example, the relationship between saturation temperature and pressure, the enthalpy of saturated liquid as a function of temperature, the entropy of saturated liquid as a function of temperature, the enthalpy of superheated steam as a function of temperature and pressure and the entropy of superheated steam as a function of enthalpy and pressure. An algebraic expression for each of these relationships was found using least-squares curve-fitting techniques with Steam Table data. The resulting expressions are given in the detailed description of the power plant model in Appendix D. The results predicted by these expressions are within 5 percent of the Steam Table values, over the domain of independent variables considered.

In practice, additional components such as reheaters and feedwater extraction regenerative heaters are included in the steam cycle to

increase its efficiency. The model can approximately predict the performance of an extraction steam cycle by including the following two factors in the model: (1) ratio of Rankine cycle efficiency of the extraction cycle to the Rankine cycle efficiency of the simple cycle operating under the same fuel input and turbine-steam supply conditions, R_{eff} , and (2) the ratio of flow rate of steam through the boiler to flow rate of condensate through the condenser for the extraction cycle, R_f . If both of these factors have a value of 1, the simple cycle performance will be calculated by the model.

Representative values of these factors were found as a function of turbine inlet steam pressure, P_b , by analyzing the performance data from ten coal-fired TVA power plants having generator capacities ranging from 150 MW to 914 MW and utilizing steam pressures at the turbine inlet from 1800 psi to 3500 psi. From these data, it was found that the simple cycle model could be used to predict quite accurately the performance of extraction cycles using the above-mentioned factors as calculated from the following correlations with boiler pressure:

$$R_{eff} = 1.027 + (5.3214 \times 10^{-5} \text{ psia}^{-1})P_b \quad (\text{III-27})$$

$$R_f = 0.896 + (3.214 \times 10^{-4} \text{ psia}^{-1})P_b \quad (\text{III-28})$$

With these correlations, accurate comparison of the performance and costs between large utility-sized coal-burning and wood-burning power plants can be made.

A correlation for parasitic power, P_{para} , as a function of gross electrical power output, P_g , for coal-fired power plants is reported on pg. B-163 of Reference 43 to be:

$$P_{para} = 4.6 \text{ MW } (P_g/100 \text{ MW})^{0.86} \quad (\text{coal-fired plant}) \quad (\text{III-29})$$

From performance data for these coal-fired plants, it was estimated that 50 percent of the parasitic power in the coal plant is used in the fuel delivery system and the other 50 percent is used in the remainder of the power plant. It was further estimated that the fuel delivery system in a wood-fired power plant requires three times the power of the fuel delivery system in a coal-fired plant, and that the remaining portion of the power plant is common to both types. Under these assumptions, the parasitic power for a wood-fired plant becomes twice that for the coal-fired plant; i.e.,

$$P_{\text{para}} = 9.2 \text{ MW } (P_g/100 \text{ MW})^{0.86} \quad (\text{wood-fired plant}) \quad (\text{III-30})$$

Installation costs and operation and maintenance costs for large coal-fired power plants are reported in Reference 44. Algebraic expressions for these costs are as follows:

$$\text{Installation cost (1976 dollars)} = 39.9 \times 10^6 + 390 P_g \text{ (kW)} \quad (\text{III-31})$$

$$\text{Operation and maintenance cost (1976 dollars)} = 1.63 \times 10^6 + 2.22 P_g \text{ (kW)} \quad (\text{III-32})$$

The above expression for operation and maintenance costs gives costs that are 7% higher than those reported, to convert the costs from 1975 dollars to 1976 dollars.

From examination of the cost data for coal-fired power plants reported in Reference 43, it was estimated that ten percent of the cost is for fuel-handling equipment and the remaining 90% is for the remaining power generation equipment. Assuming the fuel-handling equipment for a wood-fired power plant costs three times as much as the fuel-handling equipment for a coal-fired power plant and the costs for the remainder of the power plants are equal, the costs for a wood-fired power plant are 20 percent higher than those for a coal-fired plant of the same size. On this basis, cost equations for large-size wood-fired power plants are as follows:

$$\text{Installation cost (1976 dollars)} = 47.9 \times 10^6 + 468 P_g \text{ (kW)} \quad (\text{III-33})$$

$$\text{Operation and maintenance cost (1976 dollars)} = 1.96 \times 10^6 + 2.66 P_g \text{ (kW)} \quad (\text{III-34})$$

Installation costs for smaller-sized wood-fired power plants were furnished by Mr. S. Hunter W. Brooks, a consulting engineer on the project. His design of a demonstration wood-fired power plant is presented in Appendix G. This design shows a relatively large parasitic power ratio. Mr. Brooks indicates, however, that these parasitic power requirements could be reduced to the order of 10 percent of the generated electrical power output with more efficient fuel-handling systems, at an increased installation cost of about 10 percent. These lower parasitic power values are in very good agreement with those given by equation III-30. Hence, for smaller sized wood-fired plants, the cost data from Appendix G were increased by 10 percent to yield the following correlation:

$$\text{Installation cost (1976 dollars)} = 18.7 \times 10^6 + 806 P_g \text{ (kW)} \quad (\text{III-35})$$

Equations III-33 and III-35 for installation costs for wood-fired power plants yield the same cost at a power output of 86,400 kW. Hence, equation III-33 is used for installation costs of power plants producing 86,400 kW or more and equation III-35 is used to calculate installation costs for power plants producing less than 86,400 kW. Using the above equations as a basis, the model calculates the cost per unit of electricity by each of the financing methods described in Appendix A.

A complete list of the input and output parameters and the equations used in the power plant model is presented in Appendix D.

4. System Performance at Potential Sites

At each of the 15 selected PEF sites, an average cost, delivery rate and moisture content of Energy PlantationTM fuel for the optimum-sized plantation was determined from the results of the Energy PlantationTM model calculations. These values were then fed into the power plant model, with which the performance of the power plant and the cost of electricity generated by the power plant were calculated. The power plant load factor at each site was determined by examining published data for the utility serving that site. A fuel composition was estimated from data on Page 22 of Reference 45. The high heating value of the fuel was set at the same value used in the Energy PlantationTM model calculations, viz., 8600 Btu/oven-dry pound. Thus, the generator output calculated for each site corresponds to the required capacity of a power plant operating under the given conditions of yearly fuel supply and load factor.

For each site both a "low-performance" steam cycle and a "high-performance" steam cycle were analyzed. The low-performance cycle is considered to represent the present-day wood-burning boiler technology. This is a simple Rankine cycle with steam supplied at a pressure of 650 psia and a temperature of 750°F, and a turbine having an efficiency of 79%. The high-performance cycle is considered representative of what could be accomplished with higher performance equipment comparable to that used in utility power plant systems. This is an extraction cycle with steam supplied at a pressure of 2400 psia and a temperature of 1000°F, and a turbine having an efficiency of 90%. For both cycles, a moisture content of 20% (wet basis) was specified for the fuel leaving the dryer, and an exhaust gas temperature of 200°F was specified for the exhaust gas leaving the dryer. A steam-condensing temperature of 125°F was specified, so that the cooling water could be heated to a high enough value (115°F) to be of benefit to the algae pond. The conditions of the combustion air supply were assumed to be 70% excess at a temperature of 70°F and a relative humidity of 45% (specific humidity of 0.007).

A sample computer printout for one site (Bemidji, Minnesota) is included as Table III-24. The more significant results of the calculations for all 15 sites are summarized in Table III-25. These results show costs ranging from 70 mills/kWh to 107 mills/kWh as calculated by the utility method of financing for electricity generated by the low-performance steam cycle. At the other end of the spectrum, the costs calculated by the municipal method of financing for electricity generated by the high-performance steam cycle range from 35 mills/kWh to 53 mills/kWh.

The results show a significant correlation between electricity costs and load factor with the cost decreasing as load factor increases. To illustrate this effect, cost versus load factor for a 162-MW plant in Natchitoches is plotted in Figure III-19. Also plotted on the figure are the points for the demonstration plants for the lowest cost electricity at Jamestown, New York, where the load factor is 68 percent, and the highest-cost electricity at Kissimmee, Florida, where the load factor is only 20 percent. It is evident that the power plant economics are generally more favorable at sites where higher load factors prevail.

The capacities of the above power plants are very small by utility standards. To examine the economy-of-scale effect of Energy-PlantationTM produced electricity, different-sized "high-performance" power plants were analyzed at one location where an intermediate electricity cost prevails, viz. Natchitoches, Louisiana. The resulting costs as a function of generating capacity are shown in Figure III-20. These show a marked economy-of-scale effect, with "utility-method" costs dropping from 67 mills/kWh at 160 MW capacity to 53 mills/kWh at 600 MW capacity and "municipal-method" costs dropping from 43 mills/kWh to 32 mills/kWh over the same range of generator capacities, and dropping slightly more to 31 mills/kWh at 1000 MW. Both costs show a slight tendency to increase as generator capacity increases above 1200 MW, with a more pronounced increase shown in utility-method costs. Below

600 MW there are a few discontinuities in the fuel costs, due to a "mismatch" between plantation size and harvesting equipment capacity, which could cause slight "ripples" in the electricity cost curve. Above 600 MW, these mismatches are not pronounced, and the fuel cost decreases monotonically with generator capacity. The slight increase in electricity costs calculated by the model at high generator capacities is attributed to the increase in "interest-during-construction" costs, which arise from the "built-in" increase in construction time calculated by the model. It is concluded that in order to take full advantage of the economy of scale, the power plant should have capacity of at least 500 MW.

To compare these estimated costs involved in generating electricity from wood with those for generating electricity from coal, the power plant model was used to calculate costs for new coal-fired plants. The fuel composition was changed, the fuel dryer was excluded, and the coal-fired plant cost correlations were used in these calculations. The same high-performance power cycle was assumed as that for the high-performance wood-fired plant, and the Natchitoches load factor of 33 percent was used. Fuel costs of \$1.00 and \$1.50 per 10^6 Btu (\$26.60 and \$39.90 per ton, respectively) were used to illustrate the influence of this factor.

The results are plotted in Figure III-20. The results show that the costs of electricity from a municipally financed power plant burning wood biomass from a PEF are comparable to such costs of a plant burning low-sulfur coal. Utility-method costs for a wood-fired plant are somewhat higher than such costs for coal-fired plants due to the higher cost of the wood fuel under such conditions. To keep the costs of wood-generated electricity down, a municipality or some other governmental entity might be interested in financing the Energy PlantationTM to provide cheaper fuel for a utility-owned power plant.

If the Natchitoches plant were actually operated at a high load factor of 80 percent, the costs for PEF-generated electricity and coal-generated electricity would be essentially equal. For a plant of 1,000 MW, for example, the cost of electricity from a PEF plant would be 31 mills/kWh (utility method) versus 27 mills/kWh from a coal plant. With municipal financing, the costs would be 20 mills/kWh and 21 mills/kWh, respectively. With municipal financing, the cost of biomass fuel from a PEF is cheap enough to offset the greater capital cost of the PEF power plant over that of a coal-fired power plant to make the electricity cheaper.

This comparison between costs of electricity generated from wood and coal probably illustrates the relative differences quite accurately because the same model (with appropriate changes in the cost correlations and the fuel characteristics) was used for both cases, eliminating any bias which may be contained in the model. Cost estimates can be influenced significantly by the parameters assumed in the financial analysis so that cost estimates from different sources may not be on a comparable basis.

For example, for the financial analyses in this work, the assumption of a 20-year plant life was used with a 20-year period for depreciation. If the plant life is assumed to be 30 years instead, then the cost of electricity is lowered by perhaps 15 percent in the case of utility costs and perhaps 8 percent in the municipal case. Also, in the analyses in this work, no investment tax credit was assumed.

TABLE III- 24
COMPUTER PRINTOUT OF POWER PLANT MODEL FOR
BEMIDJI, MINNESOTA

a) Low-Performance Steam Cycle

POWERPLANT PERFORMANCE CALCULATION

240832. POUNDS PER HOUR OF FUEL SUPPLIED AT 73. DEG F,
52.00 PERCENT MOISTURE (WET BASIS) AND 1.00 PERCENT DIRT.

HIGHER HEATING VALUE OF OVEN DRY FUEL = 8600. BTU PER POUND.

OVEN DRY FUEL ANALYSIS:

50.40 PERCENT CARBON
6.10 PERCENT HYDROGEN
40.50 PERCENT OXYGEN
8.00 PERCENT NITROGEN
3.00 PERCENT ASH

BOILER PERFORMANCE:

OVERALL HEAT TRANSFER COEFFICIENT-AREA PRODUCT = 533527. BTU PER HOUR DEG F

142692. POUNDS PER HOUR OF FUEL SUPPLIED AT 20.00 PERCENT MOISTURE (WET BASIS).

1202042. POUNDS PER HOUR (73. PERCENT EXCESS) OF AIR SUPPLIED
AT A TEMPERATURE OF 584. DEG F AND 0.0070 SPECIFIC HUMIDITY.

1340168. POUNDS PER HOUR OF FLUE GAS AT A FLAME TEMPERATURE OF 3030. DEG F
AND LEAVING AT A TEMPERATURE OF 950. DEG F.

206709. POUNDS PER HOUR OF CARBON DIOXIDE
117086. POUNDS PER HOUR OF OXYGEN
916729. POUNDS PER HOUR OF NITROGEN
99564. POUNDS PER HOUR OF WATER VAPOR

565629. POUNDS PER HOUR OF STEAM SUPPLIED AT 650. PSIA AND 750. DEG F
(255. DEG F SUPERHEAT).

3425. POUNDS PER HOUR OF ASH REMOVED

1142. POUNDS PER HOUR OF UNBURNED CARBON REMOVED

DRYER AND SCREENER PERFORMANCE:

90311. POUNDS PER HOUR OF WATER REMOVED FROM FUEL.

3010. POUNDS PER HOUR OF DIRT AND 4817. POUNDS PER HOUR OF FUEL
AT 20.00 PERCENT MOISTURE (WET BASIS) REMOVED IN SCREENING PROCESS.

142692. POUNDS PER HOUR OF FUEL AT 20.00 PERCENT MOISTURE (WET BASIS) DELIVERED TO STORAGE.

0. POUNDS PER HOUR OF TEMPERING AIR SUPPLIED AT A TEMPERATURE OF 70. DEG F.

1475717. POUNDS PER HOUR OF EXHAUST GAS LEAVING AT TEMPERATURES OF 200. DEG F DRY BULB AND
126. DEG F WET BULB.

213769. POUNDS PER HOUR OF CARBON DIOXIDE
121038. POUNDS PER HOUR OF OXYGEN
947673. POUNDS PER HOUR OF NITROGEN
193236. POUNDS PER HOUR OF WATER VAPOR

POWERPLANT PERFORMANCE CALCULATION

1282480. POUNDS PER HOUR OF DRY EXHAUST GAS.

MOLECULAR WEIGHT OF DRY EXHAUST GAS = 30.2

VOLUMETRIC ANALYSIS OF DRY EXHAUST GAS:

11.44 PERCENT CARBON DIOXIDE

8.90 PERCENT OXYGEN

79.66 PERCENT NITROGEN

AIR PREHEATER PERFORMANCE:

OVERALL HEAT TRANSFER COEFFICIENT-AREA PRODUCT = 463691. BTU PER HOUR DEG F

AIR ENTERING AT 70. DEG F AND LEAVING AT 584. DEG F

FLUE GAS ENTERING AT 850. DEG F AND LEAVING AT 419. DEG F

CONDENSER PERFORMANCE:

52315. THOUSAND POUNDS PER HOUR OF COOLING WATER SUPPLIED AT 105. DEG F,
RETURNED AT 115. DEG F

565628. POUNDS PER HOUR OF STEAM CONDENSING AT 1.91 PSIA AND 125. DEG F.

OVERALL HEAT TRANSFER COEFFICIENT-AREA PRODUCT = 36261908. BTU PER HOUR DEG F.

ENERGY PLANTATION CALCULATIONS:

115598. POUNDS PER HOUR OF FUEL AT 49.0 PERCENT OVEN DRY FUEL REQUIRED AT
A LOAD FACTOR OF 48.0 PERCENT.

AN AVERAGE CUTTING RATE OF 58. TONS PER HOUR NEEDED FOR HARVESTING
24 HOURS PER DAY, 245 DAYS PER YEAR.

8219. THOUSAND CUBIC FEET NEEDED TO STORE ENOUGH FUEL AT A DENSITY OF
30.0 OVEN DRY POUNDS PER CUBIC FOOT FOR 90 DAYS OF POWERPLANT OPERATION.

26821. ACRES OF ENERGY PLANTATION NEEDED TO PROVIDE 56643. POUNDS PER HOUR
OF OVEN DRY FUEL AT AN AVERAGE YIELD RATE OF 9.3 OVEN DRY TONS PER ACRE PER YEAR.

POWERPLANT PERFORMANCE CALCULATION

POWERPLANT ENERGY BALANCE:

ENERGY INPUT RATE TO POWERPLANT	=	1014.86 MILLION BTU PER HOUR
UNBURNED FUEL LOSS	=	33.14 MILLION BTU PER HOUR
ENERGY INPUT RATE TO BOILER	=	981.72 MILLION BTU PER HOUR
TOTAL LOSSES IN BOILER	=	257.58 MILLION BTU PER HOUR
UNBURNED CARBON LOSS	=	16.08 MILLION BTU PER HOUR
RADIATION AND UNACCOUNTED FOR LOSS	=	29.45 MILLION BTU PER HOUR
SENSIBLE HEAT LOSS	=	115.88 MILLION BTU PER HOUR
LATENT HEAT LOSS	=	96.16 MILLION BTU PER HOUR
FROM WATER IN FUEL	=	30.09 MILLION BTU PER HOUR
FROM HYDROGEN IN FUEL	=	66.07 MILLION BTU PER HOUR
ENERGY INPUT RATE TO STEAM	=	724.14 MILLION BTU PER HOUR
BOILER EFFICIENCY	=	73.76 PERCENT
ENERGY INPUT RATE TO COOLING WATER	=	523.15 MILLION BTU PER HOUR
TURBINE POWER OUTPUT	=	200.99 MILLION BTU PER HOUR
TURBINE EFFICIENCY	=	79.00 PERCENT
RANKINE CYCLE EFFICIENCY	=	27.76 PERCENT
GENERATOR OUTPUT	=	57689.33 KILOWATTS
GENERATOR EFFICIENCY	=	98.00 PERCENT
IN-PLANT POWER	=	5732.31 KILOWATTS
PARASITIC POWER RATIO	=	9.94 PERCENT
NET POWER OUTPUT	=	51957.02 KILOWATTS
POWERPLANT EFFICIENCY	=	17.48 PERCENT
ENERGY TRANSFER RATE IN AIR PREHEATER	=	143.18 MILLION BTU PER HOUR
ENERGY TRANSFER RATE IN DRYER	=	95.22 MILLION BTU PER HOUR
RATIO OF DRYING TO PLANT INPUT ENERGY	=	9.38 PERCENT

POWERPLANT COST SUMMARY

CAPITAL COST IN MILLIONS OF 1976 DOLLARS =
18.7 + 886. TIMES GENERATOR OUTPUT IN MILLIONS OF KILOWATTS.

OPERATION AND MAINTENANCE COST IN MILLIONS OF 1976 DOLLARS =
1.96 + 2.66 TIMES GENERATOR OUTPUT IN MILLIONS OF KILOWATTS.

FUEL COSTS = 22.18 (UTILITY) 16.98 (MUNICIPAL) 1976 DOLLARS PER OVEN DRY TON.

FACTORS USED IN UTILITY METHOD OF FINANCING:

FRACTION OF COSTS FINANCED BY BORROWED CAPITAL = 65.8 PERCENT.
RATE OF RETURN ON BORROWED CAPITAL = 9.8 PERCENT.
DESIRED AFTER-TAX RATE OF RETURN ON EQUITY = 15.8 PERCENT.

COMPOSITE DISCOUNTING RATE = 11.108 PERCENT.

RATE OF RETURN FOR MUNICIPAL METHOD OF FINANCING = 6.375 PERCENT.

INVESTMENT PERIOD = 20 YEARS.

GENERATOR OUTPUT = 57689.33 KILOWATTS.

ANNUAL ELECTRICITY OUTPUT = 242.57 MILLION KILOWATT HOURS.

ANNUAL FUEL REQUIREMENT = 248897. OVEN DRY TONS.

LOAD FACTOR = 48.88 PERCENT.

COSTS (MILLIONS OF 1976 DOLLARS)	UTILITY METHOD	MUNICIPAL METHOD
CAPITAL	65.28	65.28
LAND AND WORKING CAPITAL	1.27	1.85
INTEREST DURING CONSTRUCTION (2.0 YEARS)	7.19	4.13
ANNUAL COSTS		
OPERATION AND MAINTENANCE	2.11	2.11
FUEL	5.48	4.19
DEPRECIABLE INVESTMENT	9.15	6.23
NONDEPRECIABLE INVESTMENT	8.14	8.87
FEDERAL INCOME TAX	1.98	----
TOTAL REVENUE REQUIRED	18.87	12.68
PRODUCT COST (1976 DOLLARS PER KILOWATT HOUR)	8.878	8.852

TABLE III-24
COMPUTER PRINTOUT OF POWER PLANT MODEL FOR
BEMIDJI, MINNESOTA

b) High-Performance Steam Cycle

POWERPLANT PERFORMANCE CALCULATION

248830. POUNDS PER HOUR OF FUEL SUPPLIED AT 70. DEG F,
50.00 PERCENT MOISTURE (WET BASIS) AND 1.00 PERCENT DIRT.

HIGHER HEATING VALUE OF OVEN DRY FUEL = 8600. BTU PER POUND.

OVEN DRY FUEL ANALYSIS:

50.40 PERCENT CARBON
6.10 PERCENT HYDROGEN
40.50 PERCENT OXYGEN
0.00 PERCENT NITROGEN
3.00 PERCENT ASH

BOILER PERFORMANCE:

OVERALL HEAT TRANSFER COEFFICIENT-AREA PRODUCT = 692825. BTU PER HOUR DEG F

142692. POUNDS PER HOUR OF FUEL SUPPLIED AT 20.00 PERCENT MOISTURE (WET BASIS).

1202042. POUNDS PER HOUR (70. PERCENT EXCESS) OF AIR SUPPLIED
AT A TEMPERATURE OF 346. DEG F AND 0.0070 SPECIFIC HUMIDITY.

1340168. POUNDS PER HOUR OF FLUE GAS AT A FLAME TEMPERATURE OF 2830. DEG F
AND LEAVING AT A TEMPERATURE OF 650. DEG F.

206789. POUNDS PER HOUR OF CARBON DIOXIDE
117086. POUNDS PER HOUR OF OXYGEN
916729. POUNDS PER HOUR OF NITROGEN
99564. POUNDS PER HOUR OF WATER VAPOR

784896. POUNDS PER HOUR OF STEAM SUPPLIED AT 2400. PSIA AND 1000. DEG F
(330. DEG F SUPERHEAT).

3425. POUNDS PER HOUR OF ASH REMOVED

1142. POUNDS PER HOUR OF UNBURNED CARBON REMOVED

DRYER AND SCREENER PERFORMANCE:

90311. POUNDS PER HOUR OF WATER REMOVED FROM FUEL.

3010. POUNDS PER HOUR OF DIRT AND 4817. POUNDS PER HOUR OF FUEL
AT 20.00 PERCENT MOISTURE (WET BASIS) REMOVED IN SCREENING PROCESS.

142692. POUNDS PER HOUR OF FUEL AT 20.00 PERCENT MOISTURE (WET BASIS) DELIVERED TO STORAGE.

0. POUNDS PER HOUR OF TEMPERING AIR SUPPLIED AT A TEMPERATURE OF 70. DEG F.

1475717. POUNDS PER HOUR OF EXHAUST GAS LEAVING AT TEMPERATURES OF 200. DEG F DRY BULB AND
126. DEG F WET BULB.

213769. POUNDS PER HOUR OF CARBON DIOXIDE
121030. POUNDS PER HOUR OF OXYGEN
947673. POUNDS PER HOUR OF NITROGEN
193236. POUNDS PER HOUR OF WATER VAPOR.

POWERPLANT PERFORMANCE CALCULATION

1282480. POUNDS PER HOUR OF DRY EXHAUST GAS.

MOLECULAR WEIGHT OF DRY EXHAUST GAS = 38.2

VOLUMETRIC ANALYSIS OF DRY EXHAUST GAS:

11.44 PERCENT CARBON DIOXIDE

8.90 PERCENT OXYGEN

79.66 PERCENT NITROGEN

AIR PREHEATER PERFORMANCE:

OVERALL HEAT TRANSFER COEFFICIENT-AREA PRODUCT = 235346. BTU PER HOUR DEG F

AIR ENTERING AT 70. DEG F AND LEAVING AT 346. DEG F

FLUE GAS ENTERING AT 650. DEG F AND LEAVING AT 419. DEG F

CONDENSER PERFORMANCE:

41005. THOUSAND POUNDS PER HOUR OF COOLING WATER SUPPLIED AT 185. DEG F,
RETURNED AT 115. DEG F

470742. POUNDS PER HOUR OF STEAM CONDENSING AT 1.91 PSIA AND 125. DEG F.

OVERALL HEAT TRANSFER COEFFICIENT-AREA PRODUCT = 28422452. BTU PER HOUR DEG F

ENERGY PLANTATION CALCULATIONS:

115598. POUNDS PER HOUR OF FUEL AT 49.0 PERCENT OVEN DRY FUEL REQUIRED AT
A LOAD FACTOR OF 48.0 PERCENT.

AN AVERAGE CUTTING RATE OF 58. TONS PER HOUR NEEDED FOR HARVESTING
24 HOURS PER DAY, 245 DAYS PER YEAR.

8219. THOUSAND CUBIC FEET NEEDED TO STORE ENOUGH FUEL AT A DENSITY OF
30.0 OVEN DRY POUNDS PER CUBIC FOOT FOR 90 DAYS OF POWERPLANT OPERATION.

26821. ACRES OF ENERGY PLANTATION NEEDED TO PROVIDE 56643. POUNDS PER HOUR
OF OVEN DRY FUEL AT AN AVERAGE YIELD RATE OF 9.3 OVEN DRY TONS PER ACRE PER YEAR.

POWERPLANT PERFORMANCE CALCULATION

POWERPLANT ENERGY BALANCE:

ENERGY INPUT RATE TO POWERPLANT	=	1014.86 MILLION BTU PER HOUR
UNBURNED FUEL LOSS	=	33.14 MILLION BTU PER HOUR
ENERGY INPUT RATE TO BOILER	=	981.72 MILLION BTU PER HOUR
TOTAL LOSSES IN BOILER	=	257.58 MILLION BTU PER HOUR
UNBURNED CARBON LOSS	=	16.08 MILLION BTU PER HOUR
RADIATION AND UNACCOUNTED FOR LOSS	=	29.45 MILLION BTU PER HOUR
SENSIBLE HEAT LOSS	=	115.88 MILLION BTU PER HOUR
LATENT HEAT LOSS	=	96.16 MILLION BTU PER HOUR
FROM WATER IN FUEL	=	30.09 MILLION BTU PER HOUR
FROM HYDROGEN IN FUEL	=	66.07 MILLION BTU PER HOUR
ENERGY INPUT RATE TO STEAM	=	724.14 MILLION BTU PER HOUR
BOILER EFFICIENCY	=	73.76 PERCENT
ENERGY INPUT RATE TO COOLING WATER	=	410.05 MILLION BTU PER HOUR
TURBINE POWER OUTPUT	=	314.09 MILLION BTU PER HOUR
TURBINE EFFICIENCY	=	90.00 PERCENT
RANKINE CYCLE EFFICIENCY	=	43.37 PERCENT
GENERATOR OUTPUT	=	90611.06 KILOWATTS
GENERATOR EFFICIENCY	=	98.50 PERCENT
IN-PLANT POWER	=	8452.08 KILOWATTS
PARASITIC POWER RATIO	=	9.33 PERCENT
NET POWER OUTPUT	=	82158.98 KILOWATTS
POWERPLANT EFFICIENCY	=	27.64 PERCENT
ENERGY TRANSFER RATE IN AIR PREHEATER	=	76.75 MILLION BTU PER HOUR
ENERGY TRANSFER RATE IN DRYER	=	95.22 MILLION BTU PER HOUR
RATIO OF DRYING TO PLANT INPUT ENERGY	=	9.38 PERCENT

POWERPLANT COST SUMMARY

CAPITAL COST IN MILLIONS OF 1976 DOLLARS =
47.9 + 468. TIMES GENERATOR OUTPUT IN MILLIONS OF KILOWATTS.

OPERATION AND MAINTENANCE COST IN MILLIONS OF 1976 DOLLARS =
1.96 + 2.66 TIMES GENERATOR OUTPUT IN MILLIONS OF KILOWATTS.

FUEL COSTS = 22.10 (UTILITY) 16.90 (MUNICIPAL) 1976 DOLLARS PER OVEN DRY TON.

FACTORS USED IN UTILITY METHOD OF FINANCING:

FRACTION OF COSTS FINANCED BY BORROWED CAPITAL = 65.0 PERCENT.
RATE OF RETURN ON BORROWED CAPITAL = 9.0 PERCENT.
DESIRED AFTER-TAX RATE OF RETURN ON EQUITY = 15.0 PERCENT.

COMPOSITE DISCOUNTING RATE = 11.100 PERCENT.

RATE OF RETURN FOR MUNICIPAL METHOD OF FINANCING = 6.375 PERCENT.

INVESTMENT PERIOD = 20 YEARS.

GENERATOR OUTPUT = 90611.06 KILOWATTS.

ANNUAL ELECTRICITY OUTPUT = 381.00 MILLION KILOWATT HOURS.

ANNUAL FUEL REQUIREMENT = 248097. OVEN DRY TONS.

LOAD FACTOR = 48.00 PERCENT.

COSTS (MILLIONS OF 1976 DOLLARS)	UTILITY METHOD	MUNICIPAL METHOD
CAPITAL	90.31	90.31
LAND AND WORKING CAPITAL	1.28	1.07
INTEREST DURING CONSTRUCTION (2.1 YEARS)	10.66	6.12
ANNUAL COSTS		
OPERATION AND MAINTENANCE	2.20	2.20
FUEL	5.48	4.19
DEPRECIABLE INVESTMENT	12.76	8.66
NONDEPRECIABLE INVESTMENT	0.14	0.07
FEDERAL INCOME TAX	2.74	----
TOTAL REVENUE REQUIRED	23.33	15.13
PRODUCT COST (1976 DOLLARS PER KILOWATT HOUR)	0.061	0.040

TABLE III-25 : SITE COMPARISON OF POWERPLANT PERFORMANCE
AND GENERATED ELECTRICITY COSTS

Site	Load Factor (percent)	Delivered Fuel Cost (1976 dollars/oven-dry ton)		Cycle*	Generator Capacity(MW)	Cycle Efficiency (percent)	Electricity Cost (1976 mills/kWh)	
		Utility Method	Municipal Method				Utility Method	Municipal Method
Bemidji, MN	48	22.10	16.90	L	57.7	17.5	78	52
				H	90.6	27.6	61	40
Caldwell, TX	43	27.73	19.99	L	70.1	17.3	86	56
				H	110.2	27.3	66	42
Chanute, KS	40	25.72	18.43	L	76.1	17.3	87	56
				H	119.5	27.3	66	42
Greenwood, SC	47	25.60	18.80	L	56.1	18.6	82	54
				H	88.0	29.5	64	41
Hammond, NY	46	24.83	18.95	L	64.9	18.8	79	52
				H	102.0	29.7	61	39
Jamestown, NY	68	26.05	19.45	L	41.6	18.3	70	48
				H	65.3	28.9	53	35
Kissimmee, FL	20	23.43	17.63	L	165.8	18.7	107	68
				H	260.4	29.5	87	53
Knoxville, TN	42	34.71	23.53	L	46.2	18.6	102	67
				H	72.6	29.4	79	50
Martinsville, VA	51	25.22	18.65	L	56.2	18.6	77	51
				H	88.2	29.5	60	39
Maysville, KY	76	33.95	23.59	L	25.2	18.0	86	58
				H	39.7	28.5	62	41
Minden, LA	34	26.25	19.17	L	95.3	18.4	90	58
				H	149.7	29.1	68	43
Natchitoches, LA	33	24.23	18.58	L	103.4	18.1	88	57
				H	162.4	28.6	67	43

TABLE III-25(continued)

Pensacola, FL	51	27.98	20.04	L	48.6	18.3	83	55
				H	76.3	29.0	64	41
Traverse City, MI	62	32.63	22.96	L	42.2	17.4	82	55
				H	66.2	27.5	62	40
Yazoo City, MS	39	25.84	19.01	L	67.1	18.3	90	59
				H	105.3	29.0	69	44

* L= low-performance cycle, H= high-performance cycle

FIGURE III-19: ELECTRICITY COST VS. LOAD FACTOR
FOR WOOD-FIRED POWER PLANTS

FIGURE III-20: FUEL AND ELECTRICITY COSTS FOR WOOD-FIRED POWER PLANT AT NATCHITOCHES, LA., AND AVERAGE ELECTRICITY COSTS FOR COAL-FIRED POWER PLANTS VS. GENERATOR CAPACITY

5. Sensitivity Analysis of Low-Performance Cycle

To examine the effects of changing certain controllable conditions on the performance of the power plant, a sensitivity analysis was performed for the low-performance cycle on the following parameters: (1) moisture content of delivered fuel and dry fuel, (2) temperature and pressure of steam produced by the boiler, (3) isentropic turbine efficiency, and (4) excess air supply. The base-case conditions for these values were as follows:

Delivered-fuel moisture content	- 50 percent (wet basis)
Dried-fuel moisture content	- 20 percent (wet basis)
Steam pressure	- 650 psia
Steam temperature	- 750°F
Excess air supply	- 40 percent
Isentropic turbine efficiency	- 79 percent

where the value for turbine efficiency was chosen for a 60-MW turbine operating with steam at 650 psia and 750°F.

The results of these sensitivity analyses are presented in Table III- 26 and Figures III-21, 22 and 23, respectively. The results of the moisture analysis show that performance is essentially independent of dried-fuel moisture content, except for the cases where no drying is done. The reason for the decrease in performance for the no-drying cases is that the screened-out fuel fines are not utilized, hence their heating value represents a net energy loss to the powerplant. There is a significant increase in performance with a decrease in delivered-fuel moisture content from 50 percent down to 20 percent. With a further decrease in delivered-fuel moisture content, little or no increase in performance is noted.

The power plant performance increases substantially with increases in steam pressure and temperature, and with increases in turbine efficiency. These effects are also apparent in the differences in performance between

TABLE III-26
POWERPLANT EFFICIENCY
VS.
WET-BASIS FUEL MOISTURE CONTENT

Delivered Fuel Moisture Content (percent)	Dry Fuel Moisture Content (percent)					
	<u>50</u>	<u>40</u>	<u>30</u>	<u>20</u>	<u>10</u>	<u>0</u>
50	15.8	16.9	16.9	16.9	16.9	16.9
40	--	17.1	17.9	18.0	18.0	18.0
30	--	--	18.0	18.6	18.7	18.7
20	--	--	--	18.7	19.1	19.3
10	--	--	--	--	19.2	19.6
0	--	--	--	--	--	19.6

Exhaust Gases Leaving Powerplant at 200°F
Steam Generated at 650 psia, 750°F
40 percent excess air
79 percent turbine efficiency

FIGURE III-21: POWERPLANT EFFICIENCY vs. BOILER EXIT PRESSURE WITH
BOILER EXIT TEMPERATURE AS A PARAMETER

FIGURE III-22: POWERPLANT EFFICIENCY vs. ISENTROPIC TURBINE EFFICIENCY

FIGURE III-23: POWERPLANT EFFICIENCY vs. EXCESS AIR

the low-performance and high-performance cycles reported in Table III-25, as these parameters are those upon which the difference in these two types of cycles is based.

As the excess air supply increases from 40 percent to 100 percent, the power plant efficiency decreases by 0.3 percent, from 16.9 percent to 16.6 percent.

IV. PEF SYSTEM PERFORMANCE AND POTENTIAL

A. Operation of PEF Model for Potential Sites

As described in the preceding section, the subsystem models which compose the comprehensive techno-economic PEF model were exercised for the fifteen potential demonstration sites. These results were presented in terms of single systems operating independently with certain external inputs and, indeed, these results were calculated in exactly this manner with the individual subsystem models. The sensitivity analyses for these subsystem models show which parameters and variables are most influential and how system performance can be improved and at what cost.

However, the results of the site analyses for the three subsystems must be combined to show what a complete demonstration PEF will look like and to illustrate the magnitude of the interactions within a PEF at a site. This analysis is useful in assessing the impact of a PEF of a certain design and size at a potential site. This overall analysis will also be an aid in selecting the best sites for a demonstration.

Table IV-1 lists the important characteristics of a complete PEF demonstration project at each site being considered. For the algae pond, the table shows the characteristics of an algae pond subsystem designed to produce algae up to the carbon limit in the wastewater. In the detailed discussion of the algae pond subsystem it was shown that, at the present time, it is not cost-effective to design the algae pond to produce algae up to the phosphorus limit, with carbonation. Such a system may be cost-effective in the future with development of appropriate technology and only a moderate reduction in cost.

It should be noted that the area of the algae pond is a very small fraction of the area of the Energy PlantationTM. The algae pond was sized to handle the wastewater flow from each population center, and the Energy PlantationTM

TABLE IV- 1

CHARACTERISTICS OF POTENTIAL DEMONSTRATION PEF'SCarbon-Limited Design of Algae Pond System

<u>Site</u>	<u>Algae Pond</u>		<u>Energy PlantationTM</u>					
	<u>Wastewater</u> <u>Flow</u> <u>MGD</u>	<u>Acres</u>	<u>Gas</u> <u>Produced</u> <u>10⁶ SCF/YR</u>	<u>Fertilizer</u> <u>Produced</u> <u>Tons N/YR</u>	<u>Fertilizer</u> <u>Purchased</u> <u>Tons N/YR</u>	<u>Acres</u>	<u>Productivity*</u> <u>Tons/Acres-YR</u>	<u>Production**</u> <u>10³ Tons (O.D.)/YR</u>
Kissimmee, FL	1.3	20	4.15	42.7	2941	36,000	7.06	262
Pensacola, FL	6.0	101	19.1	197.0	2058	24,000	8.00	198
Chanute, KS	1.1	22	2.65	27.1	3020	36,000	7.45	277
Maysville, KY	0.7	13	1.67	17.2	1731	36,000	4.12	153
Natchitoches, LA	1.8	40	5.75	59.1	3093	36,000	7.55	279
Minden, LA	1.5	34	4.8	49.2	2941	36,000	7.04	261
Traverse City, MI	1.8	38	2.87	29.5	2734	36,000	6.32	232
Bemidji, MN	1.1	21	2.04	21.1	2960	27,000	9.05	250
Yazoo City, MS	1.1	27	3.51	36.1	2351	36,000	5.62	209
Hammond, NY	1.5	54	3.18	32.8	2778	36,000	6.37	237
Jamestown, NY	4.0	144	8.5	87.6	2586	33,000	6.59	225
Greenwood, SC	2.1	46	6.71	68.9	2253	30,000	6.50	201
Knoxville, TN	17.0	487	54.2	558.1	1176	33,000	4.41	150
Caldwell, TX	0.36	6	1.15	11.8	3009	36,000	7.38	275
Martinsville, VA	2.5	62	7.98	82.1	2441	30,000	7.06	218

* Average based on above-ground biomass.

** Average annual sustained production includes contribution of root mass produced upon replanting.

TABLE IV-1 (Continued)

	Load Factor percent	Power Plant			
		Simple Cycle		Efficient Cycle	
		Capacity MW	Production 10 ⁶ KWH/YR	Capacity MW	Production 10 ⁶ KWH/YR
Kissimmee, FL	20	166	290.5	260	456.3
Pensacola, FL	51	49	216.9	76	340.7
Chanute, KS	40	76	266.7	120	418.8
Maysville, KY	76	25	168.1	40	264.0
Natchitoches, LA	33	103	298.9	162	469.4
Minden, LA	34	95	283.8	150	445.7
Traverse City, MI	62	42	229.1	66	359.8
Bemidji, MN	48	58	242.6	91	381.0
Yazoo City, MS	39	67	229.1	105	359.9
Hammond, NY	46	65	261.6	102	411.0
Jamestown, NY	68	42	247.8	65	389.2
Greenwood, SC	47	56	230.8	88	362.5
Knoxville, TN	42	46	170.0	73	267.1
Caldwell, TX	43	70	264.4	110	415.2
Martinsville, VA	51	56	251.0	88	394.2

was sized to produce solid fuel at an optimally low cost. This ratio of algae pond area to Energy PlantationTM area is an important quantity which determines the extent of the influence of the algae pond upon the Energy PlantationTM.

Table IV-1 shows the amount of SNG which can be produced by the algae pond system at each potential site. These quantities of gas are relatively small compared to the total market for gas at each site. However, these quantities of gas are perhaps twice as much as the net amount of gas typically produced from an anaerobic digestion in a conventional wastewater treatment plant; it has been assumed that waste heat from the power plant rather than part of the gas produced is used to heat the digester.

The economic optimum for the size of an Energy PlantationTM unit, in terms of the cheapest fuel produced, is from 24,000 to 36,000 acres. The estimated productivities of these demonstration Energy PlantationsTM vary from 4.1 to over 9 dry tons per acre-year. This productivity is estimated for production of above-ground material on an average sustained basis. The annual production figure given includes the contribution of root mass obtained from replanting operations and also takes into account the material utilized for clones for replanting.

The table shows the capacity and the production of power plants using off-the-shelf equipment for a demonstration plant and of power plants using technology which can be borrowed from coal-fired plants (although a wood-fired plant using it would have to be specially designed).

Table IV-2 shows the economics of a demonstration PEF at the potential sites under the assumption of municipal financing. The table shows the capital costs for the three PEF subsystems as well as the annualized

TABLE IV-2

ECONOMICS OF POTENTIAL DEMONSTRATION PEF'S

Carbon-Limited Design of Algae Pond System, Municipal Financing

Site	Algae Pond		Energy Plantation TM		
	Capital Cost \$10 ⁶	Total Annual Cash Flow* \$10 ⁶	Capital Cost \$10 ⁶	Total Annual Cost \$10 ⁶	Cost of Fuel \$/Ton (O.D.)
Kissimmee, FL	0.814	0.300	25.13	4.73	17.63
Pensacola, FL	2.279	1.602	5.27	4.06	20.04
Chanute, KS	0.786	0.150	31.39	5.10	18.43
Maysville, KY	0.592	0.027	23.29	3.75	23.59
Natchitoches, LA	1.100	0.421	7.34	5.28	18.58
Minden, LA	0.981	0.343	6.87	5.15	19.17
Traverse City, MI	1.087	0.131	8.81	5.32	22.96
Bemidji, MN	0.782	0.021	7.47	4.22	16.90
Yazoo City, MS	0.834	0.235	6.53	4.05	19.01
Hammond, NY	1.143	0.165	7.55	4.54	18.95
Jamestown, NY	2.155	0.374	7.10	4.48	19.45
Greenwood, SC	1.203	0.504	6.07	3.89	18.80
Knoxville, TN	5.883	4.619	5.76	3.72	23.53
Caldwell, TX	0.389	0.056	27.10	5.49	19.99
Martinsville, VA	1.395	0.612	6.18	4.21	18.65

* A positive cash flow, rather than an annualized cost, because of the wastewater treatment credit.

TABLE IV- 2 (Continued)

	Power Plant							
	Simple Cycle				Efficient Cycle			
	Capital Cost \$10 ⁶	Total Annual Cost, \$10 ⁶	Cost of Electricity \$/KWH	\$/KWH (with crd.)	Capital Cost \$10 ⁶	Total Annual Cost, \$10 ⁶	Cost of Electricity \$/KWH	\$/KWH (with crd.)
Kissimmee, FL	125.50	19.62	0.068	0.067	169.78	24.36	0.053	0.052
Pensacola, FL	57.83	11.91	0.055	0.048	80.16	14.14	0.041	0.036
Chanute, KS	80.04	15.01	0.056	0.055	103.84	17.46	0.042	0.042
Maysville, KY	39.05	9.69	0.058	0.058	50.67	10.84	0.041	0.041
Natchitoches, LA	96.29	17.10	0.057	0.056	123.90	20.00	0.043	0.042
Minden, LA	92.49	16.50	0.058	0.057	117.94	19.16	0.043	0.042
Traverse City, MI	52.69	12.56	0.055	0.054	72.09	14.49	0.040	0.040
Bemidji, MN	65.20	12.60	0.052	0.052	90.31	15.13	0.040	0.040
Yazoo City, MS	72.75	13.43	0.059	0.058	97.20	15.91	0.044	0.043
Hammond, NY	71.03	13.73	0.052	0.051	95.63	16.23	0.039	0.039
Jamestown, NY	52.23	11.81	0.048	0.047	71.37	13.72	0.035	0.034
Greenwood, SC	63.88	12.44	0.054	0.052	89.11	14.97	0.041	0.040
Knoxville, TN	55.95	11.32	0.067	0.040	77.21	13.44	0.050	0.033
Caldwell, TX	75.26	14.92	0.056	0.056	99.49	17.39	0.042	0.042
Martinsville, VA	63.98	12.78	0.051	0.049	89.20	15.31	0.039	0.037

costs. The annualized cash flow from the algae pond is a positive cash flow resulting from the applicable wastewater treatment credit.

The cost of electricity produced from the power plant is shown before and after the wastewater treatment credit is applied to reduce the overall cost of operating the entire PEF. For sites such as Knoxville and Pensacola, which have the largest ratio of algae pond area (dependent upon available wastewater) to Energy PlantationTM area, the reduction in electricity cost can be significant. For the more efficient power plant, the cost of electricity, with the credit applied, of 40 mills per kilowatt-hour or so, should be attractive to rural areas, which are now paying the highest rates for electricity transmitted over a large distance from a large central power plant operated by a large utility.

Table IV-3 shows the total costs for demonstration PEFs at the potential sites. The total capital cost is shown, and the total net annualized cost after the application of the wastewater treatment credit. The total capital investment required for a demonstration is, of course, larger than the total capital cost because the investment would include interest during construction, start-up expenses, and working capital.

One important interaction between the algae pond system and the Energy PlantationTM in a PEF is the contribution of fertilizer from the algae pond. Table IV-4 presents data which illustrate this interaction in detail, both with present technology in operating a carbon-limited algae pond and with future technology in operating a phosphorus-limited system. This table shows the amount of nitrogen fertilizer produced by the algae pond at each site and the resultant reduction in cost of biomass produced, the fertilizer being valued at its equivalent in ammonium nitrate. The reduction in the cost of biomass can be significant if there is sufficient wastewater, such as is the case at Knoxville and Pensacola. A phosphorus-limited algae pond system could produce about 5.4 times as much nitrogen fertilizer as a carbon-limited system, which demonstrates the potential for developing the necessary technology.

TABLE IV-3

TOTAL COSTS FOR DEMONSTRATION PEF'sCarbon-Limited Design of Algae Pond System, Municipal Financing

<u>Site</u>	Simple-Cycle Power Plant		Efficient-Cycle Power Plant	
	Total Capital Cost, \$10 ⁶	Total Annual Cost*, \$10 ⁶	Total Capital Cost, \$10 ⁶	Total Annual Cost*, \$10 ⁶
Kissimmee, FL	151.44	24.05	195.72	28.79
Pensacola, FL	65.38	14.37	87.71	16.60
Chanute, KS	112.22	19.96	136.02	22.41
Maysville, KY	62.93	13.41	74.55	14.56
Natchitoches, LA	104.73	21.96	132.34	24.86
Minden, LA	100.34	21.31	125.79	23.97
Traverse City, MI	62.59	17.75	81.99	19.68
Bemidji, MN	73.45	16.80	98.56	19.33
Yazoo City, MS	80.11	17.24	104.56	19.72
Hammond, NY	79.72	18.11	104.32	20.60
Jamestown, NY	61.48	15.92	80.62	17.83
Greenwood, SC	71.15	15.83	96.38	18.36
Knoxville, TN	67.59	10.42	88.85	12.54
Caldwell, TX	102.76	20.35	126.99	22.82
Martinsville, VA	71.56	16.38	96.78	18.91

*Includes credit for treatment of wastewater.

TABLE IV-4

CHARACTERISTICS OF ALGAE POND SYSTEMS IN A DEMONSTRATION PEF

Site	Wastewater Flow, MGD	Carbon-Limited Algae Pond			Reduction in Fertilizer Cost per Ton \$/Ton	Phosphorus-Limited Algae Pond			Reduction in Fertilizer Cost per Ton \$/Ton	Energy Plantation™ Purchased Fertilizer Tons N/YR
		Acres	Gas	Fertilizer		Acres	Gas	Fertilizer		
			10 ⁶ SCF/YR	Tons N/YR			10 ⁶ SCF/YR	Tons N/YR		
Kissimmee, FL	1.3	20	4.15	42.7	0.07	156	22.9	229.4	0.38	2941
Pensacola, FL	6.0	101	19.1	197.0	0.43	789	106.0	1058.8	2.31	2058
Chanute, KS	1.1	22	2.65	27.1	0.04	175	14.7	145.6	0.21	3020
Maysville, KY	0.7	13	1.67	17.2	0.04	103	9.3	92.6	0.22	1731
Natchitoches, LA	1.8	40	5.75	59.1	0.08	317	31.9	317.6	0.43	3093
Minden, LA	1.5	34	4.80	49.2	0.07	264	26.6	264.7	0.38	2941
Traverse City, MI	1.8	38	2.87	29.5	0.05	300	15.9	158.8	0.27	2734
Bemidji, MN	1.1	21	2.04	21.1	0.03	167	11.3	113.2	0.16	2960
Yazoo City, MS	1.1	27	3.51	36.1	0.07	212	19.4	194.1	0.38	2351
Hammond, NY	1.5	54	3.18	32.8	0.07	422	17.6	176.5	0.38	2778
Jamestown, NY	4.0	144	8.5	87.6	0.19	1127	47.1	470.6	1.02	2586
Greenwood, SC	2.1	46	6.71	68.9	0.15	359	37.1	370.6	0.81	2253
Knoxville, TN	17.0	487	54.2	558.1	1.60	3806	300.0	3000.0	3.37	1176
Caldwell, TX	0.36	6	1.15	11.8	0.02	51	6.4	63.5	0.11	3009
Martinsville, VA	2.5	62	7.98	82.1	0.16	482	44.2	441.2	0.86	2441

In Table IV-4, only nitrogen is considered; this is the most important fertilizer in terms of quantity and cost. However, the algae pond also contributes significant quantities of phosphorus and potassium as well. In Knoxville, for example, the entire phosphorus requirement of the Energy PlantationTM can be met with the fertilizer produced from the algae pond.

The results of the model calculations are useful in evaluating and ranking potential sites for a demonstration. Some important attributes of sites for a potential demonstration are low cost--both capital cost and operating cost. Other attributes are the magnitude of the fertilizer contribution--the higher, the better to demonstrate this important PEF interaction--and the difference in cost of the electricity produced by the PEF and the current local cost--the smaller this difference, the sooner the demonstration will be cost-effective.

Data were obtained on local cost of electricity (Table II-7), but as these data are a couple of years old, the cost of electricity is undoubtedly higher now. In the discussion of the power plant model, it was shown that the cost of PEF-generated electricity is comparable to that of electricity generated from coal in a new plant. The rising cost of fossil fuel will make the PEF more cost-competitive within a short period of time. Indeed, with a life-cycle cost analysis with the estimated increases in cost of fossil-fuel-generated electricity, a PEF with a power plant operating on a "high-performance" cycle may be cost-effective now. Such an analysis would be useful to make in the next study to design a demonstration PEF. In any case, a demonstration PEF should be planned now for implementation in the near future so that this technology will be proven by the time that it is needed.

Table IV-5 shows how the 15 potential sites for a demonstration PEF can be ranked according to four attributes of an effective PEF demonstration.

TABLE IV-5
RANKING OF SITES FOR A POTENTIAL DEMONSTRATION PEF

	<u>Low Capital Cost</u>	<u>Low Operating Cost</u>	<u>Magnitude of Fertilizer Contribution from Algae Pond</u>	<u>Low Difference in Cost of Electricity</u>	<u>Overall Rank</u>
1	Jamestown	Knoxville	Knoxville	Pensacola	Pensacola
2	Traverse City	Maysville	Pensacola	* { Jamestown	Jamestown
3	Maysville	Pensacola	Jamestown		Knoxville
4	Pensacola	Greenwood	Martinsville	Hammond	Martinsville
5	Knoxville	Jamestown	Greenwood	Bemidji	Greenwood
6	Greenwood	Martinsville	Natchitoches	Greenwood	Maysville
7	Martinsville	Bemidji	Minden	* { Traverse City	Traverse City
8	Bemidji	Yazoo City	Yazoo City		Hammond
9	Hammond	Traverse City	Kissimmee	Chanute	Bemidji
10	Yazoo City	Hammond	Hammond	Maysville	Yazoo City
11	Minden	Chanute	Traverse City	* { Natchitoches	Natchitoches
12	Caldwell	Caldwell	Maysville		Minden
13	Natchitoches	Minden	Chanute	* { Yazoo City	Chanute
14	Chanute	Natchitoches	Bemidji		Kissimmee
15	Kissimmee	Kissimmee	Caldwell	Minden	Caldwell

* Tie

The overall rank was determined simply by adding up the ranks of the four separate attributes and listing the sites in terms of ascending value (but decreasing rank). For further, more detailed consideration of a suitable site for a demonstration PEF, the top five sites might be included. It should, perhaps, be noted that the top five sites represent a wide range of geographical locations, and a wide range of other variables as well.

In this short analysis of potential sites, Pensacola, Florida, appears to be the top choice from a number of points of view, but other candidates should be carried along for further study as well to allow for the inclusion of influential, site-specific variables which may dictate the final choice. With the methodology that has been developed in this project for evaluating sites, other sites not considered here can be quickly evaluated and included in the later analysis if found to have special virtues.

B. General Objectives of Proposed PEF Demonstration Project

The overall objectives of a PEF Demonstration Project would be to demonstrate the economics and technology of growing plant matter purposely for its fuel value on a large scale according to the Energy PlantationTM and PEF concepts, and of using this plant matter to generate electricity which can be introduced in a reliable fashion into a utility power grid. The Energy PlantationTM concept seeks to maximize the total annual sustained yield of plant matter per acre at minimum cost through proper design and operation. Although current or near-term technology is involved in all parts of this concept, plant matter has never been produced in this fashion for the purpose of producing fuel, and the actual economics have never been demonstrated.

The projected economics of the PEF Energy PlantationTM compare favorably with current economics of some fuels, such as oil, and near-term economics of other fuels, such as coal, while the concept offers numerous advantages. Although the Energy PlantationTM appears to be economically viable in the near term, reservations do exist about some of its features which are unique, and these reservations, which prevent widespread implementation of the concept, must be resolved with a demonstration project. Suggested specific objectives of demonstrating the Energy Plantation subsystem of PEF, aimed at resolving these questions, are shown in Table IV-6.

The objectives of demonstrating the algae production subsystem of PEF should be more oriented toward research and development. The technology of some of the parts of this subsystem is far from being developed or proven, and the economics of the algae production subsystem are less certain now than the economics of the Energy PlantationTM. Thus, the algae subsystem should be designed with the idea of using it to develop and to prove the technology, by doing critical experiments and revising the system as data are obtained.

TABLE IV-6
SUGGESTED SPECIFIC DEMONSTRATION OBJECTIVES OF ENERGY PLANTATIONTM SUBSYSTEM

1. Use of "marginal" land
2. Use of land on a large scale
3. Yields and plantation design
4. Advantages of deciduous species, effects on yields and economics
 - a. Fast juvenile growth
 - b. Multiple harvests through coppicing
 - c. Reproduction with clones
5. Mechanization of plantation operations
6. Sustained yields over a period of time
7. Maintenance of productivity of land
8. Water requirements
9. Material handling operations

Specific research areas for an algae pond system in a demonstration PEF fall into two basic categories: (1) development of technical data and operational experience and (2) development of less expensive process equipment or procedures. The growth ponds are a good example of this need for parallel research. On the one hand, it is necessary to develop operational experience with high-rate algal growth ponds to improve the solar conversion efficiency. Similarly, it is necessary to obtain operational experience with methods of maintaining blue-green algae cultures. This involves experimentation with hydraulic and solids recycle procedures. A parallel effort is necessary in reducing pond construction cost. Innovative pond arrangements are already being developed, and low-cost technologies are being explored. The construction costs are primarily related to excavation, and hence research needs to be done on developing pond configurations with minimum excavation costs on land which is not level.

A similar parallel research effort is necessary on the flue-gas carbonation system. It is first necessary to study the effect of flue-gas carbon dioxide on the pond ecosystem. Assuming the carbon dioxide transfer proves feasible and no deleterious effects of trace materials in the flue gas are noted, it will also be necessary then to develop a low-cost sparging system. The sensitivity analysis indicates that the primary method of reducing cost in the sparging system is to improve its transfer efficiency.

New technical and economic data are also required in the digestion step. It will be necessary to quantify further the effect of heating the digester to different temperatures. Also, a much clearer understanding of the mass flow and nutrient balances around the digester system must be developed. Finally, work has already been started on developing cost estimates for fermentation ponds which would be much less costly than conventional tank digesters. These ponds would be equipped with floating gas domes which could be made of plastic. The potential cost-tradeoff between the lower capital cost and the anticipated lower gas yield (due to lack of mixing) must be studied.

While various harvesting procedures have been experimented with, none has a clear-cut advantage at this point in providing reliable, low-cost harvesting of algae. Further work must be done in this area.

In all cases, it would appear that the most effective way of developing new technology, for an algae pond system, would be through small demonstrations of the entire system. In this manner the interaction of the various subsystems can be studied. For example: should algae species control be accomplished, microstrainers would then become a wholly suitable method of harvesting. Since, in many of the research areas, the development work is directed toward cost reduction of full-size equipment, it seems imperative to use full-scale equipment for testing.

Our assessment indicates that cost-effective gas production with pond recarbonation is an attainable near-term goal. On this basis, a nitrogen-limited demonstration facility would be invaluable (1) for providing pond and carbonation system operating experience and (2) for providing the research facility for species control techniques. When the land availability problem is considered, a design flow of about 5 MGD seems advisable. Of the sites identified, Pensacola most nearly meets the guidelines for selecting a demonstration site.

C. Potential of the PEF Concept and Future Developments

As the result of this work to study the concept of the Photosynthesis Energy Factory, we have developed a general techno-economic model of such an integrated bioconversion system and have exercised this model to investigate some of the possible interactions between the PEF's various subsystems. We have also collected data on various sites throughout the country which appear to have potential as sites for a possible demonstration system. Finally, to complete the work, we have used the model to assess the impact of a PEF at each of fifteen potential sites. For each site, a preliminary design of a demonstration PEF has been developed by means of the model, and the amount of fuel produced at each site and its production cost have been estimated.

The analysis which we have performed so far indicates that some interactions between the PEF are generally cost-effective while others are probably site-specific or can be improved upon. In addition, we have conceived of various improvements which may be made both in the model and in the analysis of the applicability of PEF. In the present work, for example, neither the potential irrigation of the Energy PlantationTM with reclaimed wastewater nor the heating of the algae pond was considered. These potential interactions of the PEF subsystems should be studied to extend the synergy of the concept. Furthermore, the current model has been developed to include conventional technology available today. The model should be expanded and refined to include near-term technology to represent more accurately the potential of the PEF concept.

Low-cost irrigation of the Energy PlantationTM is an important possible extension of the PEF concept which has several ramifications. First of all, irrigation of the Energy PlantationTM with reclaimed wastewater from the algae pond would allow the PEF concept to be implemented at locations naturally too dry for an Energy PlantationTM by itself. A wastewater flow of 1 MGD would perhaps supply the complete water requirement for 6,000 oven-dry tons of annual production. In most cases, the wastewater flow would probably be a supplementary supply of water to augment the natural supply (no possible site of any interest has absolutely no rainfall,

although Las Vegas has only four inches annually).

Second, irrigation could possibly improve the use of fertilizer by allowing it to be distributed onto the plantation whenever it is needed, annually, rather than in one large dose at harvest time. The one large dose, which is calculated to supply several years' worth of fertilizer, will undergo some degradation and loss. Thus, the fertilizer requirement, which is a significant expense, could perhaps be reduced by using an irrigation system to distribute it. This would be a credit which could offset some of the cost of the irrigation system.

Finally, an irrigation system could also be useful in allowing wastewater to be applied directly (after primary sedimentation) to the dry land Energy PlantationTM. Viewed in a larger perspective, the Photosynthesis Energy Factory is a bioconversion system which integrates material and resource recycling with biomass production for fuel. There are various alternative processes which may be used to accomplish these general goals. An algae pond system is only one possible biosystem which can accomplish material and resource recycling with energy recovery.

The synergy inherent in the overall PEF concept can be preserved with direct application of wastewater to the Energy PlantationTM. The nutrients such as nitrogen and phosphorus are made available to the growing plants. Water is recycled in a useful way. The wastewater treatment credit, which is the most important economic benefit of the algae pond to the PEF, would apply to the Energy PlantationTM directly, helping to pay for the irrigation system and to lower the cost of the biomass produced. As for recycle of the carbon dioxide evolved from the power plant, our analysis indicates that with current technology, carbonation of algae ponds to increase the yield of algae from wastewater by tying up nitrogen and phosphorus, is not cost-effective at the present time. Indeed, the technology needed

for doing so is not developed. At the present time, no data exist to show any increase in productivity of algae ponds (tons per acre-year) due to carbonation.

Our estimated energy balances show that the net energy recovery per acre-year (gross energy yield less needed energy input, without energy conservation credits) for the Energy PlantationTM (about 130×10^6 Btu per acre-year based on eight tons production, less five percent) is about twice that for the algae pond (about 66×10^6 Btu per acre-year, based on ten tons production, Table III-1). The Energy PlantationTM thus fixes carbon more efficiently than the algae pond. In addition, the Energy PlantationTM does not need special carbonation equipment to utilize carbon dioxide in the air (flue gas); it does so naturally. Thus, for growing biomass by utilizing the carbon dioxide in flue gas, an acre of dry-land Energy PlantationTM produces greater energy yield than an acre of algae pond at significantly lower cost, with present technology.

Of course, the energy from an algae pond system is in the form of SNG, which is more desirable as a fuel than the solid fuel from an Energy PlantationTM. However, the SNG from an algae pond is costly, according to our current estimates, and technology and cost reduction innovations are necessary. It should certainly be possible, however, to obtain SNG from Energy PlantationTM biomass, but of course, costs are unknown and technology is undeveloped in this area. Work should be done to recover SNG from juvenile woody biomass.

The potential exists, according to the University of California at Berkeley, for increasing the productivity and hence the energy recovery, from an algae pond system. Doubling the productivity from 10 to 20 tons per acre-year would increase the net energy yield from 66 to 166 million Btu per acre-year in the form of SNG--certainly a desirable goal which should be pursued, particularly since algae can possibly have a more highly valued purpose than use as fuel.

However, it is the purpose of this discussion to point out that at least one alternative exists to including the algae pond in the PEF for the purpose of recycling materials and resources and achieving the synergy inherent in the PEF concept. This alternative, viz., direct land application of wastewater, appears to have significant advantages and should be analyzed in parallel with the algae pond in later projects to develop the PEF concept further.

Further work should be done to define the possible improvements in algae pond technology that can be brought to bear on the PEF concept. These possible developments should be analyzed in the context of the PEF model to evaluate their potential usefulness in improving the PEF and to determine feasible goals for their development.

The economics of the PEF concept can be improved significantly if ways can be found to improve the efficiency of using Energy PlantationTM biomass as a solid fuel. Thus, biomass can perhaps be used in an admixture with coal to take advantage of biomass' unique properties. Different types of combustion equipment should be investigated. The major problem however in using biomass as a solid fuel is to devise a way of either getting the water out of the fuel before combustion or recovering the latent heat in the water vapor in the flue gas.

Overall, the results of this first project in analyzing the usefulness of the PEF concept show that there is value in some of the interactions which are possible in a PEF system. The results also indicate where potential exists for improving the concept, and these indicated approaches should be explored to develop the Photosynthesis Energy Factory into a more cost-effective alternate energy sources and energy recovery system.

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VI. APPENDIX

- A. Economic Analysis: Utility and Municipal Financing
- B. Details of Algae Pond System Model
- C. Plant Growth Characterization
- D. Details of Power Plant Model
- E. Requests for Information from State Energy Offices
- F. Analyses of Wood Samples
- G. Design of Demonstration Wood-Fired Power Plant
- H. Report on Algae Pond System from University of California at Berkeley
(Separate Report)

APPENDIX A

ECONOMIC ANALYSIS: UTILITY AND MUNICIPAL FINANCING

I. INTRODUCTION

The economic analysis of the Photosynthesis Energy Factory and its component parts has been carried out with two types of financing -- first, the so-called utility method and, second, municipal financing. The two types of financing apply to different situations. It is conceivable, depending on circumstances and the size of the system, that a PEF could be built and operated by a private utility or by a municipality. Because different interest rates, methods of financing, and tax laws apply to these two situations, the cost of the power produced may be significantly different. Thus, because one objective of this project is to determine where and under what conditions the PEF would be especially cost-effective in producing biomass for power generation, both types of financing have been used in the economic analysis.

The following discussion presents the basic principles used in the economic analysis with these two types of financing. One presentation in the literature of the utility method of financing which is widely quoted¹ uses some approximations which introduce error into the analysis. The procedure described here is based upon the calculation of annual equivalent costs for the various cash flows using the more exact equations² rather than approximations. Of course, the accuracy of the final answers is still influenced by the accuracy of the estimated costs used as input data and the validity of the assumptions, but at least any error due to the procedure is eliminated.

¹Esso Research and Engineering Company, "Description and Gas Cost Calculation Methods Being Used by the Synthetic Gas-Coal Task Force of the FPC National Gas Survey," 1972.

²G.W. Smith, "Engineering Economy: Analysis of Capital Expenditures," Iowa State University Press, 1968.

II. UTILITY METHOD OF FINANCING

Any financial analysis uses as basic input the results of the cost analysis of a project. These costs are then combined and analyzed depending upon the method of financing to determine the revenue required per unit of product over the project lifetime to produce the desired rate of return on invested capital under the applicable tax conditions. The required project data are:

1. Depreciable Investment (DI) -- includes investment for equipment and buildings, etc.; interest during construction (IDC); and startup (SU), if included.
2. Nondepreciable Investment (NDI) -- land, and working capital, which is estimated as 1/6 of annual operating costs.
3. Annual operating costs (AOC).
4. Financial structure -- fraction debt D at a certain interest rate i_D (e.g., 0.65 at 0.09 rate of interest) and fraction equity E at a desired after-tax rate of return i_E (e.g., 0.35 at 0.15 rate of return).
5. Period of investment n for analysis purposes for the whole project or a piece of equipment -- e.g., 20 years.
6. Method of depreciation -- assumed to be straight line; fractional depreciation allocation in any year = $1/n$.
7. Number of units of product sold per year (NO UNITS).

The calculation of annual equivalents proceeds as follows:

1. Calculation of utility rate of return i_U :

$$i_U = Di_D + Ei_E$$

2. Calculation of annual equivalent of capital recovery to provide repayment of capital and return on capital for depreciable investment, the rate of return being the utility rate of return:

$$AEDI = \frac{i_U (1 + i_U)^n DI}{(1 + i_U)^n - 1}$$

where n is the lifetime of the particular investment being considered. A building might last the lifetime of the project, but a piece of equipment might last only a few years.

(The capital recovery is frequently approximated as the sum of depreciation plus return on average investment, the average investment being based on straight-line depreciation. However, the necessary capital recovery can be significantly underestimated by this approximation, as shown in Reference 2, the error being a function of the interest rate and the lifetime involved.)

3. Calculation of annual equivalent of return on nondepreciable investment:

$$AENDI = NDI i_U$$

4. Annual equivalent depreciation expense (straight line):

$$AEDE = DI/n$$

where n again might be different for different investments.

5. Annual equivalent of gross return:

$$AEGR = (AEDI - AEDE) + AENDI$$

(The annual allowable gross return is frequently estimated as $i_U (0.525 DI + NDI)$, which is lower than the correct amount (the 0.525 rather than 0.5 corrects for the calculation of depreciation at the end of the year).)

6. Annual equivalent of return on equity:

$$AERE = \frac{E i_E}{i_U} AEGR$$

7. Annual equivalent of federal income tax (the tax is assumed to be 48% of the equity earnings):

$$AEFIT = \frac{48}{52} AERE$$

8. Annual equivalent of total revenue required per year (AETR):

$$AETR = AOC + AEDI + AENDI + AEFIT$$

9. Product cost per unit:

$$PC = \frac{AETR}{\text{NO UNITS}}$$

III. MUNICIPAL FINANCING

There are several methods that a municipality can use to finance a municipally owned utility, and a detailed discussion of these various methods is outside the scope of this analysis. For purposes of comparison with the utility method, a simple procedure has been assumed. It has been assumed that the municipality raises money to finance the PEF by selling tax-free bonds with an interest rate of 6-3/8%. The municipality pays no federal income taxes on the revenue derived from operation of the PEF.

The cost data required for the municipal method of financing are the same as those required for the utility method. The calculations are, however,

greatly simplified because federal income taxes are not calculated. Thus, depreciation does not enter into the calculations.

The calculations proceed as follows:

1. Calculation of annual equivalent of capital recovery to provide repayment of capital and return on capital for depreciable investment, the rate of return being the municipal rate of return i_M (6-3/8%):

$$AEDI = \frac{i_M (1 + i_M)^n DI}{(1 + i_M)^n - 1}$$

where n is the lifetime of the particular investment being considered. A building might last the lifetime of the project, but a piece of equipment might last only a few years.

2. Calculation of annual equivalent of return on nondepreciable investment:

$$AENDI = NDI i_M$$

3. Annual equivalent of total revenue required per year (AETR):

$$AETR = AOC + AEDI + AENDI$$

4. Product cost per unit:

$$PC = \frac{AETR}{\text{NO UNITS}}$$

APPENDIX B

DETAILS OF THE ALGAE POND SYSTEM DESIGN

Appendix B contains the detailed information on the design of the algae production pond system for the PEF. The first section contains the design equations for each of the subroutines in the technical performance model. These equations cover: equipment sizing; subsystem mass and energy balances; and overall system input/output relationships.

The next section of the appendix, Table B-1, contains the equipment cost equations used for the financial analysis of the algae pond system. Except where indicated, both installed construction (capital) costs and annual operating and maintenance (O and M) costs have been presented as power functions based on a physical design parameter of the operation. This "cost parameter"--pond acreage, tank surface area, air flow, etc.--is identified for each subprocess. The base case to which actual costs are ratioed is included, as are the exponents of the cost equations.

The third section of the appendix, Table B-2, contains the references for the sources of the cost data used in developing the cost equations. Where possible, the specific process items included in the cost information are listed.

TECHNICAL DESIGN CALCULATIONS

SEDIMENTATION/THICKENING (SUBROUTINE SEDTHK)

General:

The sedimentation tanks were sized on the basis of design overflow rate. The thickener tanks were sized based on design solids loading. The following variables and equations were used to size equipment and to derive a mass flow balance for the sedimentation thickening system:

Variables:

SEDSIZ - Required surface area of sedimentation tank
SOLIDS - Total solids in sludge from sedimentation/thickener
THKSIZ - Required surface area of thickener
DRYSOL - Volatile solids in sludge
UNDRFL - Sludge mass flow from sedimentation/thickener
PSEFF - Suspended solids fractional removal efficiency in sedimentation
VSSFRC - Fraction of primary solids which are volatile
THKONC - Fraction of solids in underflow to digester
SEDOR - Design overflow rate, flow per unit surface area
TLR - Thickener loading rate, solids mass per unit area
SEWAGE - Wastewater flow
SSCONC - Suspended solids concentration in influent

Equations:

SEDIZ = SEWAGE/SEDOR (1)
THKSIZ = SOLIDS/TLR (2)
SOLIDS = SEWAGE x PSEFF x SSCONC (3)
DRYSOL = VSSFRC x SOLIDS (4)
UNDRFL = SOLIDS/THKONC (5)

ALGAE GROWTH POND CARBON BALANCE (SUBROUTINE ALCO2)

General:

The maximum algae production for a given wastewater stream was determined

by calculating the growth potential for carbon-, nitrogen-, and phosphorus-limited growth. Flue gas carbonation was included as a supplemental carbon source. Carbon dioxide from the digestion of primary solids and of algae was included in the balance. The variables and equations for these computations are listed below:

Variables:

PO4MAX - Maximum phosphorus-limited algae production
N2MAX - Maximum nitrogen-limited algae production
CEESEW - Carbon available from sewage
CEEPSD - Carbon available from primary solids CO₂
ALGAS - Conversion factor for CO₂ carbon from algae digestion
CARMAX - Maximum carbon-limited algae production
ALMAX - Maximum nutrient-limited algae production
CEEFLU - Carbon available from CO₂ in flue gas
REQCO2 - Required flue gas CO₂ flow
TRNSEF - Flue gas transfer fractional efficiency
BODOUT - Fractional overall BOD₅ removal
PO4OUT - Fractional overall phosphorus removal
NITOUT - Fractional overall nitrogen removal
BOD5 - Influent BOD₅ concentration
PHOS - Influent phosphorus concentration
NITRO - Influent nitrogen concentration
FBODPS - Fractional BOD₅ removal efficiency of primary sedimentation
FP04PS - Fractional phosphorus removal efficiency of primary sedimentation
METLB - Methane produced per pound volatiles destroyed
VSSDES - Fractional destruction of solids in digester
GRATIO - Volumetric ratio of CO₂ to methane in digester gas

Equations:

Assuming algal cells are one percent phosphorus,
$$PO4MAX = 100 \times SEWAGE \times PHOS \times (PO4OUT - FP04PS) \quad (6)$$

Assuming algal cells are ten percent nitrogen,
$$N2MAX = 10 \times SEWAGE \times NITRO \times NITOUT \quad (7)$$

Experimental data indicate 1.0 mg/l BOD5 yields 0.7 mg/l algae. Therefore,

$$CEESEW = 0.7 \times (BODOUT - FBODPS) \times BOD5 \times SEWAGE \quad (8)$$

$$CEEPSD = DRY SOL \times METLB \times GRATIO \quad (9)$$

Algae are approximately 85 percent volatile matter. Consequently,

$$ALGAS = 0.0268 \times VSSDES \times METLB \times GRATIO \quad (10)$$

Assuming algal cells are 50 percent carbon,

$$CARMAX = (CEESEW + CEEPSD)/(0.5-ALGAS) \quad (11)$$

$$CEEFLU = (0.5 \times ALMAX) - (CEESEW + CEEPSD + ALMAX \times ALGAS) \quad (12)$$

$$REQCO_2 = 3.66 \times CEEFLU/TRNSEF \quad (13)$$

If the amount of CO_2 required is more than the available supply, equation (13) must be solved for CEEFLU. Then flue gas-limited algae production is $ALMAX = (CEESEW + CEEPSD + CEEFLU)/(0.5-ALGAS)$ (14)

ALGAL YIELD (SUBROUTINE YLD2)

General:

Per-acre yield of algae is calculated using an inputted conversion efficiency of visible solar radiation. Pond area is determined by applying this conversion efficiency to the month with the lowest average daily insolation. The required pond surface area is the quotient of the monthly algal growth potential and the minimum monthly yield. The additional variables and equations necessary for the calculations appear below:

Variables:

LOWTMP - Temperature below which algal production (at constant insolation) becomes temperature dependent.

SITETH - Array for monthly temperature (degree F) and insolation (Langleys per day)

FRCVIS - Fraction of light energy in visible spectrum

SOLCON - Fraction of visible light energy captured in cell mass

ALGENR - Heat value per unit mass of algae

YLDMON - Monthly algal yield in algal mass per unit area per month

COMPAR - Lowest value of YLDMON

ANNUAL - Yield for 12 operating months

PDAREA - Required pond area

Equations:

For months where the average ambient temperature is equal to or greater than LOWTMP.

$$YLDMON = 30 \times SITETH (1,2) \times FRCVIS \times SOLCON/ALGENR \quad (15)$$

where SITETH (1,2) is the daily insolation.

$$ANNUAL = 12 \times COMPAR \quad (16)$$

$$PDAREA = (ALMAX/12)/COMPAR \quad (17)$$

CALCULATION OF REQUIRED HARVEST CYCLES (SUBROUTINE CYCLE3)

General:

The number of harvest stages required for a given site is dependent on the algae growth potential and the design algal density in the growth ponds. It corresponds to the number of ponds operated in series required to remove the limiting nutrient.

Series pond size is established by determining the area required to produce algal mass equivalent to the change in algal concentration between the pond influent and the pond effluent.

Variables and equations for the computations appear below:

Variables:

FLOOUT - Stage influent

FLOWIN - Stage effluent

AREA - Series pond size

ALCONC - Influent algal concentration

EVAPRT - Equivalent net annual evaporation

$$YLDMON = 30 \times SITETH (2) \times FRCVIS \times SOLCON/ALGENR \quad (15)$$

where SITETH (2) is the daily insolation.

$$ANNUAL = 12 \times COMPAR \quad (16)$$

$$PDAREA = (ALMAX/12)/COMPAR \quad (17)$$

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Variables and equations for the computations appear below:

Variables:

FLOOUT - Stage influent

FLOWIN - Stage effluent

AREA - Series pond size

ALCONC - Influent algal concentration

EVAPRT - Equivalent net annual evaporation

DNSMAX - Maximum allowable algal concentration

EVAPLS - Stage evaporation loss

SOLIN - Algal solids into a cell

YEELD - Stage algal production

GRODAY - Cumulative production of the series ponds

NHARV - Number of harvest stages

SIZE - Cumulative pond size

HARMAS - Cumulative harvested algae of the series ponds

NDAF - Number of dissolved air flotation stages

NMCRS - Number of microstrainer harvesting stages

ALGOUT - Fractional solids removal efficiency of harvesters

DNSMAX - Maximum allowable algal concentration
 EVAPLS - Stage evaporation loss
 SOLIN - Algal solids into a cell
 YEELD - Stage algal production
 GRODAY - Cumulative production of the series ponds
 NHARV - Number of harvest stages
 SIZE - Cumulative pond size
 HARMAS - Cumulative harvested algae of the series ponds
 NDAF - Number of dissolved air flotation stages
 NMCRS - Number of microstrainer harvesting stages
 ALGOUT - Fractional solids removal efficiency of harvesters

Equations:

$$\text{AREA} = ((\text{FLOWIN} - \text{AREA} \times \text{EVAPRT}) \times \text{DNSMAX} - \text{FLOWIN} \times \text{ALCONC})/\text{ANNUAL} \quad (18)$$

This can be rearranged to solve for the series pond size.

$$\text{AREA} = \text{FLOWIN} \times (\text{DENS MAX} - \text{ALCONC})/(\text{ANNUAL} + \text{EVAPRT} \times \text{DENS MAX}) \quad (19)$$

For each stage,

$$\text{EVAPLS} = \text{EVAPRT} \times \text{AREA} \quad (20)$$

$$\text{FLOOUT} = \text{FLOWIN} - \text{EVAPLS} \quad (21)$$

$$\text{SOLIN} = \text{ALCONC} \times \text{FLOWIN} \quad (22)$$

$$\text{YEELD} = \text{AREA} \times \text{ANNUAL} \quad (23)$$

$$\text{ALCONC} = (1 - \text{ALGOUT}) \times \text{DENS MAX} \quad (24)$$

$$\text{HARMAS} = \text{HARMAS} + \text{ALGOUT} \times (\text{SOLIN} + \text{YEELD}) \quad (25)$$

Calculation of the series pond stages continues until the theoretical algae production exceeds the algae growth potential. The size of the final

pond stage must then be recalculated to reflect the actual amount of algae to be produced.

DISSOLVED AIR FLOTATION (DAF) HARVESTERS (SUBROUTINE FLOTAN)

General:

The volume of flow to the harvesters is calculated in CYCLE3. The number of harvesting stages which will be assigned to DAF is a design input. The primary parameters in sizing the DAF system are the surface area of the DAF tanks and the the volume of air flow required.

Variables and equations for these calculations appear below:

Variables:

GASPH - CO_2 which can be added to pond water with acceptable PH change

GASGAL - CO_2 which can be added to pond water

DAFSLG - Total sludge flow from DAF units

BUBBLS - Total sparging air requirements for DAF units

TONAGE - Annual chemical usage

DAFLD - DAF unit loading rate, flow per unit area

FIZZRT - Rate of gas application, gas flow per unit flow

DAFSOL - Fraction of solids in DAF sludge

CHMDOS - DAF chemical dosage

FLO - Cumulative total of flow to DAF stages

ALG - Cumulative total of algae harvested by DAF stages

AREADF - Surface area of DAF harvesting tanks

Equations:

$$\text{DAFSLG} = \text{ALG}/\text{DAFSOL} \quad (26)$$

$$\text{AREADF} = \text{FLO}/\text{DAFLD} \quad (27)$$

$$\text{BUBBLS} = \text{FLO} \times \text{FIZZRT} \quad (28)$$

$$\text{GASGAL} = 3.16 \times \text{GASPH} \quad (29)$$

$$\text{TONAGE} = \text{FLO} \times \text{CHEMDOS} \quad (30)$$

MICROSTRAINER HARVESTERS (SUBROUTINE MICSCN)

General:

This subroutine uses the data on microstrainer harvesting stages from CYCLE3 to compute the sludge flows from, and required screen areas of, the microstrainer harvesting systems. The additional variables and equations required for the computations are presented below.

Variables:

AREAMS - Required screen area for all microstrainer units
SCRSOL - Fraction of solids in microstrainer sludge
SCRSLG - Total sludge flow from microstrainer
SCRLOD - Loading rate for microstrainers, flow per unit area
SCRALG - Cumulative total of algae mass harvested by microstrainer stages
SCRFL0 - Cumulative total flow to all microstrainer stages

Equations:

$$\text{SCRSLG} = \text{SCRALG} / \text{SCRSOL} \quad (31)$$

$$\text{AREAMS} = \text{SCRFL0} / \text{SCRLOD} \quad (32)$$

DIGESTER FOR PRIMARY AND ALGAL SOLIDS (SUBROUTINE DIGEST)

General:

Gas yield is the most important technical parameter of the digester system. The digester volume, and consequently cost, is calculated from an inputted solids retention time. The retention time is selected to provide maximum gas yield with minimum equipment size. The variables and equations for these computations appear below:

Variables:

PPHEAT - Heat from power plant condenser
ALVOL - Flow of algal volatile solids to digester
CHFOUR - Digester methane production

CO₂ - Digester carbon dioxide production

S - Minimum monthly ambient temperature during operation

HEATIN - Sensible heat requirement for heating sludge to digester operating temperature

DIVOL - Digester volume

ALGVSS - Fraction of algal solids which are volatile

RETEN - Solids retention time

LOSBTU - Methane used to heat the digester

Equations:

$$ALVOL = ALGVSS \times (DAFSLG \times DAFSOL + SCRSLG \times SCRSOL) \quad (33)$$

$$CHFOUR = VSSDES \times METLB \times (ALVOL + DRY SOL) \quad (34)$$

Assuming the sludge must be heated to the digester operating temperature (95°F),

$$HEATIN = (UNDRFL + DAFSLG + SCRSLG) \times (95 - s)$$

If insufficient heat is available from a power plant, the parasitic use of methane for digester heating is:

$$LOSBTU = (HEATIN - PPHEAT) / 1000 \quad (35)$$

$$CO_2 = CHFOUR \times GRATIO \quad (36)$$

$$DIVOL = (UNDRFL + DAFSLG + SCRSLG) \times RETEN \quad (37)$$

CO₂ SCRUBBING SYSTEM (SUBROUTINE BNFLD)

General:

The Benfield system is sized on the basis of CO₂ flow, which was calculated in the previous subroutine. Costs are a function of this flow. The remaining technical parameters of interest are the steam and power

requirements. The variables and equations for the calculations of compressor horsepower and scrubber steam and power usage are presented below:

Variables:

BNCMHP - Compressor HP for digester gas compression to 405 psi

STEMIN - Steam requirement for regenerator

PWRIN - Electrical power requirements for pumping

Equations:

For flow in SCF per day, the adiabatic horsepower is:

$$\text{BNCMHP} = 0.00214 \times (\text{CHFOUR} \times (1 + \text{GRATIO})/0.95) \quad (38)$$

$$\text{STEMIN} = (0.12 \text{ MMBTU}/1,000 \text{ SCF CO}_2) \times \text{CO}_2 \quad (39)$$

$$\text{PWRIN} = (1.2 \text{ KWH}/1,000 \text{ SCF CO}_2) \times \text{CO}_2 \quad (40)$$

POND RECARBONATION SYSTEM (SUBROUTINE SPARGE)

General:

Two systems can be used to transfer carbon dioxide to the ponds. The dissolved air flotation harvesting system can sparge flue gas. The limited amount of gas flow required, however, necessitates another sparging system. This subroutine calculates the gas flows to the sparging system based on total CO₂ requirements, DAF air flow, and CO₂ flow available from the digesters. The variables and equations for the calculations are presented below:

Variables:

FLUE - Required total flue gas flow to algae system

TRNSFR - Maximum pure CO₂ flow to DAF within pH constraints

DGLEFT - Pure CO₂ which cannot be transferred by DAF

FLUFRC - Volumetric fraction of CO₂ in flue gas

SPGAIR - Total gas which must be applied by means other than DAF

DAFAIR - Total gas flow to DAF

Equations:

$$FLUE = REQCO2/FLUFRC \quad (41)$$

If the flue gas does not already have as much CO₂ as can be transferred by DAF within PH constraints,

$$TRANSFR = (GASGAL \times FLO) - (FLUFRC/(1-FLUFRC)) \times BUBBLS \quad (42)$$

$$DGLFT = CO_2 - TRANSFR \quad (43)$$

$$SPGAIR = FLUE - (BUBBLS/(1-FLUFRC)) + DGLFT \quad (44)$$

$$DAFAIR = (BUBBLS/(1-FLUFRC)) + TRANSFR \quad (45)$$

PIPELINE GAS TREATMENT (SUBROUTINE CLENUP)

Gas treatment includes drying of the methane as it comes from the Benfield unit and compression of the dried gas to transmission pipeline pressures. The glycol dryer is a package unit. The cost is a function of the SNG flow, which has already been calculated. The gas compressor size and cost are functions of the adiabatic horsepower required for compression. If SNG flow is in SCF per day, the horsepower requirement is:

$$PIPHP = 0.0000581 \times CHFOUR \quad (46)$$

SLUDGE DRYING BEDS (SUBROUTINE DRYBED)

General:

Sludge from the digesters is air-dried prior to application on the Energy PlantationTM. The bed surface area is determined by the design solids loading rate. This subroutine calculates the surface area required for the sand beds and the quantities of nitrogen and phosphorus in the dried sludge. The variables and equations necessary for these calculations are presented in this section.

Variables:

TOTSOL - Total solids to digester

FRCSET - Fraction of settleable solids in digester influent going
to drying beds

DGSOL - Total solids to drying beds

BEDSIZ - Size of drying beds

BEDLOD - Loading rate of beds mass per day per unit area

FRTSOL - 30-percent-solids sludge to Energy PlantationTM for fertilizer

FRTPHS - Phosphorus to Energy PlantationTM

FRTNIT - Nitrogen to Energy PlantationTM

Equations:

$$TOTSOL = (UNDRFL \times THKONC) + (DAFSLG \times DAFSOL) + (SCRSLG \times SCRSOL) \quad (47)$$

$$DGSOL = FRCSET \times TOTSOL \quad (48)$$

$$BEDSIZ = DGSOL / BEDLOD \quad (49)$$

$$FRTSOL = DGSOL / 0.30 \quad (50)$$

$$FRTPHS = P04OUT \times PHOS \times SEWAGE \times ALGOUT \quad (51)$$

Nitrogen yield depends on whether or not fixation of atmospheric nitrogen occurs. The fertilizer equivalent is the larger of the following two expressions.

$$FRTNIT = NITOUT \times NITRU \times SEWAGE \times ALGOUT \quad (52)$$

$$FRTNIT = 0.1 \times ALMAX \times ALGOUT \quad (53)$$

TABLE B-1

EQUIPMENT COST EQUATIONS

EQUIPMENT	COST PARAMETER	COST EXPONENT		REFERENCE SYSTEM	REFERENCE SYSTEM COST, FALL 1976 DOLLARS	
		CAPITAL COST	O and M		CAPITAL	O and M
Sedimentation Tanks	Surface area of tank, ft ²	0.646	0.565	1-MGD Primary Treatment System (1250 ft ²)	\$ 79,500	\$5,370/yr.
Sludge Thickeners	Daily solids loading, tons/day.	≤ 5 Tons/day: 0.293	≤ 40 Tons/day: 0.215	1-MGD Primary Treatment System (0.5 Tons/day).	\$ 59,000	\$2,520/yr.
		> 5 Tons/day: 0.662	> 40 Tons/day: 1.0	1 Ton/day (extrapolated)	\$ 41,500	\$ 175/yr.
Growth Ponds	Pond surface area, acres			80-acre high-rate pond system		
- Construction		0.715			\$594,300	
- Concrete slabs		0.611			\$152,000	
- Supplies			0.5			\$2,227/yr.
- Operating labor			0.699			855 manhours/yr.
- Maintenance labor			0.434			518 manhours/yr.
Flotation Harvesters	Surface area of tank, ft ²	<1,000 ft ² : 0.569	0.576	1-MGD Phosphorus-limited Growth System (350 ft ²)	\$163,600	\$5,750/yr.
		≥1,000 ft ² : 0.875	0.857	1 square foot (extrapolated) (Chemical costs calculated separately)	\$ 580	\$28/yr.
Microstrainer	Screen surface area, ft ²	0.796	0.798	1-MGD pond system, one micro-strainer (140 ft ²)	\$ 78,000	\$3,375/yr.

TABLE B-1 (Continued)

EQUIPMENT COST EQUATIONS

EQUIPMENT	COST PARAMETER	COST EXPONENT		REFERENCE SYSTEM	REFERENCE SYSTEM COST, FALL 1976 DOLLARS	
		CAPITAL COST	0 and M		CAPITAL	0 and M
Digester	Tank volume, ft ³	<100,000 ft ³ : .333		1-MGD pond system for phosphorus-limited growth (100,000 ft ³)	\$375,000	
		≥100,000 ft ³ : .834			\$389,000	
- Supplies		< 100,000 ft ³ : 0.283				\$4,045/yr.
- Operating labor		0.129				940 manhours
- Maintenance labor		0.811				627 manhours
- Supplies		> 100,000 ft ³ 0.722				\$4,256/yr.
- Operating labor		0.829				890 manhours
- Maintenance labor		0.811				570 manhours
Gas Scrubber				1-MGD pond system for phosphorus-limited growth (16 HP Compressor, 15 SCFM CO ₂)		
- Compressor	CH ₄ and CO ₂ flow, SCFM	0.581			\$ 27,460	2% of compressor
- Auxiliaries		0.459			\$ 5,280	1% of scrubber cost
- Driver		0.99			\$ 646	plus utilities
- Gear Assembly		0.335			\$ 1,600	
- Scrubber	CO ₂ flow, SCFM	0.8			\$ 13,150	
Sparging System	Sparging Gas Flow, SCFM	0.609	0.609	1-MGD pond system for phosphorus-limited growth (4500 SCFM)	\$325,000 plus header costs	8% of sparger costs

TABLE B-1 (Continued)
EQUIPMENT COST EQUATIONS

EQUIPMENT	COST PARAMETER	COST EXPONENT		REFERENCE SYSTEM	REFERENCE SYSTEM COST, FALL 1976 DOLLARS	
		CAPITAL COST	O and M		CAPITAL	O and M
Gas Clean-up System	Methane gas flow, SCFM			1-MGD pond system for phosphorus-limited growth.		
- Compressor		0.581		(3 HP Compressor, 33 SCFM Methane)	\$ 10,400	2% of Compressor Costs
- Auxiliaries		0.459			\$ 2,450	
- Driver		0.99			\$ 123	
- Gear Assembly		0.335			\$ 914	3% of Dryer Costs plus Utilities
- Glycol Dryer		0.6			\$ 6,560	
Sludge Drying Beds	Surface area, acres	0.946		1-MGD pond system for phosphorus-limited growth.	\$266,000	
- Materials and Power	Solids loading, pounds per day		0.989	(3 acres, 7000 pounds/day)		\$ 4,100
- Operational Labor			0.974			7,700 Man-hours

TABLE B-2

EQUIPMENT COST INFORMATION

<u>SUBSYSTEM</u>	<u>INCLUDED COSTS</u>		<u>TYPE AND SOURCE OF DATA</u>
	<u>CAPITAL</u>	<u>O and M *</u>	
Sedimentation Tanks	1) Excavation and backfill on a level site. 2) Inlet and sludge collecting mechanisms, circular or rectangular tank construction, skimmers, scrapers, and walkways completely installed.	1) Normal repairs and preventive maintenance. 2) Utilities costs. 3) Manpower for normal operation.	Empirical data. "Process Design Manual for Suspended Solids Removal," Environmental Protection Agency, EPA 625/1-75-0030, January 1975.
Gravity Thickener	Breakdown of costs was unavailable.		Stanley Consultants, "Sludge Handling and Disposal, Phase I - State of the Art," Report to the Metropolitan Sewer Board of the Twin Cities Area, 15 Nov. 1972.
High-rate Ponds	1) Stabilization pond excavation and levee construction. 2) Access road, outfall sewer, fencing, seeding and embankments. 3) Concrete work.	1) Payroll for operation, normal maintenance, administrative, and laboratory work. 2) Indirect labor costs. 3) Materials and supplies.	Empirical data. Black and Veatch, Inc., "Estimating Costs and Manpower Requirements for Conventional Wastewater Treatment Facilities," EPA 14-12-462, October 1971.

*Annual expenses for operation and maintenance

TABLE B-2 (Continued)

EQUIPMENT COST INFORMATION

<u>SUBSYSTEM</u>	<u>INCLUDED COSTS</u>		<u>TYPE AND SOURCE OF DATA</u>
	<u>CAPITAL</u>	<u>O and M</u>	
Dissolved Air Flotation	1) Installed costs of tanks and internals; recycle and air pressurizing equipment; valves; and piping. 2) Chemical feed equipment.	1) 3 percent of capital costs, excluding chemical feed equipment. 2) Chemical costs based on incutted chemical type and dosage.	Estimated costs. "Process Design Manual for Suspended Solids Removal," EPA.
Microstrainers	1) Installed costs of tanks, drums, screens, and backwash equipment. 2) Drive motors and all accessories and controls necessary for automatic operation. 3) Concrete or steel tank construction.	1) 4.3 percent of capital costs.	Estimated costs. "Process Design Manual for Suspended Solids Removal," EPA.
Digesters	1) Installed cost of digesters and control buildings. 2) Sludge heating, circulating and control equipment. 3) Piping within the structures.	1) Payroll for normal operation, maintenance, and laboratory work. 2) Materials, supplies, and utilities.	Empirical data. Black and Veatch Report

TABLE B-2 (Continued)

EQUIPMENT COST INFORMATION

<u>SUBSYSTEM</u>	<u>INCLUDED COSTS</u>		<u>TYPE AND SOURCE OF DATA</u>
	<u>CAPITAL</u>	<u>O and M</u>	
Gas Scrubber	1) Installed cost of centrifugal compressor. 2) Compressor auxiliaries drives, gear assemblies. 3) Capital cost of skid mounted Benfield CO ₂ scrubbing system.	1) Two percent of compressor costs. 2) One percent of Benfield costs. 3) Required utilities.	Estimated Costs. Guthrie, K. M., "Process Plant Estimating, Evaluation and Control," Solana Beach, California: Craftsman Book Company, 1974. Vendor quotes from The Benfield Corporation.
Spargers	1) Installed cost of diffused air aeration system piping, blowers, headers, diffusers, controls and blower building. 2) Air Distribution Header installed cost.	1) Eight percent of aeration system costs.	Empirical data. Black and Veatch Report. Estimated cost of header installation: "1972 Building Cost File" Eastern Edition, New York: Construction Publishing Company, 1971.
SNG Drying and Compression	1) Installed cost of centrifugal compressor. 2) Compressor auxiliaries drives, gear assemblies. 3) Glycol SNG drying unit installed cost.	1) Two percent of compressor costs. 2) Three percent of dryer costs. 3) Required utilities.	Estimated costs. Guthrie, K. "Process Plant Estimating, Evaluation and Control." InterTechnology Corporation, "Solar SNG: The Estimated Availability of Resources for Large-Scale Production of SNG by Anaerobic Digestion of Specially-Grown Plant Material," American Gas Association # IU 11A-1 1975.

TABLE B-2 (Continued)

EQUIPMENT COST INFORMATION

<u>SUBSYSTEM</u>	<u>INCLUDED COSTS</u>		<u>TYPE AND SOURCE OF DATA</u>
	<u>CAPITAL</u>	<u>O and M</u>	
Sludge Drying Beds.	1) Installed costs for uncovered sand beds, including excavation, distribution piping, drain beds, and under drain collection piping.	1) Payroll associated with loading, hauling and disposal of sludge, i.e. operating and maintenance requirements. 2) Materials and supplies, principally replacement of sand removed during bed cleaning process.	Black and Veatch Report.

APPENDIX C

PLANT GROWTH CHARACTERIZATION

I. INTRODUCTION

The purpose of the analysis presented in this appendix is to devise a procedure for predicting harvestable plant material yields from tree species grown in various locations and to optimize the planting and harvesting schedules for maximum sustained plant material yield per acre per year or for least cost of the biomass produced.

At first sight, it might appear unnecessary to analyze yields of plant material which can be expected from tree species grown in plantations in view of the extensive effort devoted to this subject over the years by various public and private groups concerned with pulpwood and lumber production. The problem for the Energy Plantation^R is different, however, from that faced by pulpmakers and lumbermen. In Energy Plantations, plant material is produced for its fuel value irrespective of its value as pulpwood or lumber.

The obvious approach to Energy Plantations is to consider very high planting densities (for instance, several thousand plants per acre), short growth periods before harvests (one to eight years at most), and multiple harvests, if feasible, from each planting (1). These conditions contrast sharply with the standard tree-farming techniques which generally involve less than 1,000 trees per acre, twenty years and longer harvest rotations, and only one harvest per planting. Nevertheless, this high planting density, short-rotation approach is presently investigated by pulp and paper companies, the U.S. Forest Service, and other research groups (2 to 5) in view of its potential as a source of

pulp or biomass. As will appear from the analysis in the appendix, such changes in tree-farming schedules introduce drastic changes in plantation yields and management which require an extension of the previously used yield prediction methods.

The objective of this section is to describe the analytical approach used to characterize juvenile plant growth under high-planting-density and short-rotation conditions. This section is thus the technical background on which Subroutines 2, 4 and 5 of the Energy Plantation model rest.

II. PROBLEMS ASSOCIATED WITH HIGH-INTENSITY PRODUCTION OF DECIDUOUS SPECIES

Intensive production of deciduous species for their fuel value in plantations involves three aspects of technology which depart from standard practice in the forest-products industry--high planting densities, short growth periods before harvesting, and repeated, or multiple, harvests from each planting. These departures from conventional tree-farming practice introduce new issues. They are discussed briefly in this section. Multiple harvests from a plantation are generally not feasible from evergreen plantations and thus make these species less attractive for plantation applications (6). In some cases, however, pines may be the most attractive species for a given site-climate association, and for this reason, pines are included in the present discussion.

A. High Planting Densities

Initial planting densities up to 10,000 plants per acre (about four square feet of land per plant), or more, are envisioned for Energy Plantations, in contrast to initial planting densities of 500 to 1000

trees per acre for pulpwood and lumber tree farms. These high planting densities create particular problems, of which the following two are especially important:

1. Survival rates--as the spacing between plants is made smaller, the plants will interfere with one another sooner and more intensely than they would at lower planting densities; the effects of shading of one plant by another, reduced space for leaf development, limited nutrient and water supply per plant, and higher probability of disease spreading through a plantation will tend to reduce notably the number of surviving plants after a few years--the expected increase in yield through the higher planting density will therefore be offset in part by a lower survival rate in the plantation; and
2. Growth rates--close spacing between plants will also probably adversely affect their individual growth rates, and as a consequence, lower average annual yields per plant can be expected in dense plantations than in less dense ones. However, the lower growth rate per plant is offset by the greater number of plants in a dense plantation.

B. Harvesting After Short Growing Periods

Lumber and pulpwood trees are rarely harvested before they are fifteen years old, and very often not until they are considerably older than that. While extensive yield data have been compiled for tree species of interest to the forest-products industries beginning at the age at which the trees are on the point of reaching minimum merchantable size, few data are available about their growth prior to that time. Extrapolating growth data for the period after the trees have reached merchantable size backwards, into the period prior to that time, does not give reliable estimates of growth in their first few years after planting. Consequently,

the yield tables widely used by the forest-products industry are generally not useful for estimating plant material production rates for Energy Plantations.

Fortunately, work has been underway for nearly two decades at several places on the possibility of producing short fibres for papermaking from young deciduous tree species grown in dense plantings and harvested while they are only a few years old. Many of these growth data have been made available for the analysis being discussed in this appendix. The sites at which the data have been compiled and the species involved are summarized in Table C-1. An "O" symbol indicates a site at which the data generated are sufficient to conduct a meaningful analysis of plant growth performance while an "X" indicates sites at which only limited data are generated. Each source of data will be identified when referred to in the discussion. The table thus indicates that useful data are available for a number of species grown in several areas of the United States under short-rotation and high-density conditions.

C. Multiple Harvests per Planting

After their plant material above ground has been harvested, several deciduous tree species develop sprouts from their stumps or root systems (6). Among the species displaying this trait are poplars (populus), sycamore (platanus occidentalis L.), and eastern cottonwood (populus deltoides). There are, however, at least a dozen other species which also resprout vigorously in this way. This behavior is of particular interest for Energy Plantations because it means that several harvests can be reaped from a planting, and the data available indicate that the yields of plant material from second to subsequent harvests (at least up to five or six harvests) are generally substantially higher than those from a first harvest for a given combination of species and site (2,3). To take full advantage of this multiple harvest approach in terms of the

TABLE C-1

A REPRESENTATIVE LIST OF DECIDUOUS SPECIES WHICH SHOW PROMISE FOR PLANTATION CULTURE AND LOCALITIES
WHERE THEY HAVE BEEN SHOWN TO GROW WELL IN MANAGED PLANTINGS

[illegible]

potential yield of plant material, it is necessary to develop a growth prediction procedure which relates yields from successive harvests from a planting to the land area per plant at the time of planting, the timing of the succession of harvests, and certain other factors which influence plant material yields. As mentioned earlier, pines do not generally resprout from stumps after harvest.

III. APPROACH TO THE PROBLEM OF HIGH-DENSITY, SHORT-ROTATION PLANTATIONS

The harvestable yield of plant material in oven-dry pounds per acre Y_n at year n is expressed as

$$Y_n = N_n y_n \text{ (o.d. lb/acre)} \quad (1)$$

where

N_n is the number of living plants per acre at year n which have survived from the initial number planted, N_0 , per acre

y_n is the average harvestable yield of plant material per plant at year n expressed as oven-dry pounds per plant.

The approach of expressing the yield data of tree plantations as the product of the number of surviving trees by the yield of an average, representative tree within the plantation is used by most investigators dealing with high-plantation-density, short-rotation plantations (2 to 4, 7 to 10).

Both N_n and y_n depend on a number of factors such as planting density, climate, soil quality, soil-species relationship, management of the plantation, fertilization, etc. In order to optimize the yield Y_n of a plantation, that is, in order to determine the best species to be grown

for given climate and soil conditions, the most appropriate planting density and harvest schedules, the requirement in fertilizer, etc., it is necessary to clarify as much as possible the nature of the dependence between N_n and y_n and the parameters under the plantation operator's control and those imposed on him by nature. The approach adopted here to characterize the growth properties of the species of interest is to rely as much as possible on real data from which the functional dependence of N_n and y_n on the various parameters is derived through regression analysis.

IV. PLANT SURVIVAL RATES IN HIGH-DENSITY PLANTATIONS

Analysis of the survival data for various species planted at different spacings suggests that up to about five or six years, the number of surviving plants at age n , N_n , is given by (2),

$$N_n = N_0 10^{-an} \quad (\text{trees/acre}) \quad (2)$$

where

N_0 is the number of trees planted per acre

n is the number of years since planting

a is a survival parameter having reciprocal years as its dimensions.

An equation similar to (2) has been used by Ek and Brodie (10), for aspen stands. Other functional relationships for the number of surviving plants have also been used (see (11), for instance). Fitting of the available data to equation (2) by regression analysis results in most cases analyzed in correlation coefficients (r) larger than 0.97.

The value of the survival parameter, a , depends upon a number of factors characterizing the situation considered, such as the species, the planting density, the management of the plantation, etc.

The analysis of the significant survival data leads to the following conclusions:

- a. For a given species which is well adapted to a particular plantation site, the survival parameter, a , can be expressed as a function of the area per plant at planting time,

$$a = \gamma A^{\delta} \text{ (year}^{-1}\text{)} \quad (3)$$

where γ and δ are constants,

A area per plant at planting (ft^2/tree).

The use of allometric equation (3) to express a biomass-related dependent variable (survival in this case) as a power function of an independent, measurable variable (planting area in the present case) through regression analysis is considered as the most reliable method for statistical analysis of biomass data and was adopted here. The justification and limitations of this method of analysis are discussed in reference 12. It should also be noted that the dependence of survival on planting density has been noted, but not expressed quantitatively by many authors (3, 4, 5, 12 to 32).

- b. The values of the constants γ and δ are specific to deciduous tree species and to varieties within a species. Estimated values of γ and δ are listed in Table C-2 for some of the species for which enough data are available for meaningful regression analysis.

TABLE C.-2

ESTIMATES OF THE CONSTANTS γ AND δ IN EQUATION 3 FOR SEVERAL SPECIES
GROWN UNDER VARIOUS CULTURAL TREATMENTS

<u>Species</u>	<u>Cultural Treatment</u>	<u>Estimates of γ</u>		<u>Estimates of δ</u>		<u>References</u>
		<u>Mean Value</u>	<u>Standard Deviation</u>	<u>Mean Value</u>	<u>Standard Deviation</u>	
Hybrid Poplars	Cultivated	0.03121	0.00515	-0.52745	0.13373	5,6
Sioux Cottonwood	Cultivated	0.03312	0.03179	-1.30840	0.51682	7
Silver Maple	Cultivated	0.04621	0.00488	-0.53647	0.04889	7
Black Cottonwood	Chemical weed control	0.05621	0.00516	-0.39511	0.05119	8
Missouri Cottonwood	Cultivated	0.06304	0.05474	-0.48875	0.36434	7, 9
Aspen	Not cultivated	0.07385	0.00773	-1.10372	0.18882	10,11
Pines	Some not cult., some cult., others cult. and fert.	0.08229	0.02332	-0.54365	0.07672	12
Eastern Cottonwood (P. deltoides)	Cultivated	0.11665	0.06698	-0.41118	0.11861	13 to 17
Sycamore	Cultivated and fertilized	0.20746	0.05680	-0.89112	0.08385	12, 17 to 20
Eastern Cottonwood (P. deltoides)	Cultivated and fertilized	0.24214	0.18974	-0.67466	0.15288	16
Eastern Cottonwood (P. deltoides)	Not Cultivated	0.24650	0.05858	-0.51456	0.05625	13,15,21

c. For a given species or variety, the values of the constants γ and δ depend on the cultural treatment applied to the plantation. In particular, weed control during early growth improves plant survival significantly and is therefore a necessary operation for worthwhile plantation performance. The cultural treatment referred to as "cultivated" in Table C-1 generally includes disking before planting and weed control through disking after planting. This is the most efficient cultural treatment to improve survival (23,24,29,30,34,35).

Chemical weed control has been used successfully, but caution must be exercised in the choice of the chemical agents as their use may interfere with the growth of the desired species (24,29,30,34,36).

d. Application of fertilizer at planting may have an adverse effect on the plant survival rate. An appropriate choice of the type of fertilizer used and of the schedule of application may reduce this adverse effect (23,29,33).

e. Poor site quality, as measured for instance by the site index, may increase mortality. Indications are, however, that intensive cultural treatment may offset this decrease in survival rates. Not enough reliable data exist to determine the potential effect of soil quality on survival (24,29,33).

f. Adequate moisture and good planting stock are prerequisites for high plant survival. These factors may be controlled by choosing the time of planting and selecting the planting material (37 to 43).

g. It is assumed that the number of living stumps remains essentially constant for at least five harvests subsequent to the first harvest after planting. Conflicting evidence has been reported in the litera-

ture concerning the number of surviving stumps during coppice growth (17,32,44). However, it is recognized that the yields from successive coppice harvests from a given stand remain essentially constant over the years ((45) for example). The assumption of a constant number of living stumps and associated yield per stump for coppice growth as used in equation (1) will thus adequately represent the behavior of plantation stands. It should however be noted that the assumption of a constant number of coppice stumps may have to be revised when further experimental data become available.

h. In view of the similarity of the a -versus- A relationship (equation (3)) for a substantial number of deciduous species, it is suggested that when values of γ and δ are not available for a particular species, values of γ and δ for a species having similar growing habits be used to estimate the survival rate of the species for which these values are not known.

Thus, species well-adapted to a particular site with appropriate cultural treatment display survival of 90 percent and better up to age 3 or 4 at planting densities of the order of 4 to 16 ft²/tree (about 11,000 to about 3,000 trees per acre at planting).

V. TREE GROWTH DESCRIPTION

A. Approach to the Problem

Two major approaches are used to model forest or plantation productivity. In the first approach, a single equation is postulated to describe stand growth as a function of stand parameters, such as stand basal area, and site factors, such as site index (46,47). This approach is essentially similar to that used by forest managers who rely on yield tables or functions to forecast forest productivity (48 to 50, 53, 54). This method of forecasting, however, is not suited for the prediction and analysis of forest yields under intensive management and planting conditions envisioned for short-rotation fiber or energy crop plantations. The use of yield tables in prediction is limited to stand conditions similar to those of the original sample. Also, the data in these tables seldom identify the dependence of yield on management practices such as planting densities, level of cultivation or fertilization which are essential when planning short-rotation high-density plantations.

The alternative approach is to model the behavior of individual trees grown under various management conditions and from these data to analyze and optimize stand growth conditions for highest yield, overall economics or fiber quality. This approach is generally followed by investigators studying short-rotation, dense plantations (2 to 4, 7 to 10, 51) and was adopted here (see equation (1)). A modeling approach which combines the global and individual descriptions referred to above has also been proposed: it considers the total forest ecosystem and analyzes the interaction between its individual components (soil, litter, plant components)(52). The application of the model to specific situations does require, however, a very extensive data base, which limits its usefulness as an analytical tool.

The basis for the individual-tree model used in this study is as follows. The rate of photosynthate production in a one-year period for a tree growing under a given set of conditions is

$$\frac{d(PS)}{dn} = C (LA)_n \quad (4)$$

where n is the age of the stand, (PS) is the amount of photosynthate produced, $(LA)_n$ is the leaf area at age n , and C is a constant. Analysis of experimental data led to the assumption that for young trees the leaf area can be expressed as a power function of age, thus

$$(LA)_n = A n^x \quad (5)$$

where A and x are constants. Experimental data were used to test the validity of the assumption described by equation (5). Regression analysis of leaf area data as a function of age for jack pine (14,56) and hybrid poplars (populus tristis #1)(13,57,58) resulted in values of the exponent x equal to two for six different planting densities and ages of stands up to about six years. In all cases the correlation coefficient r was 0.99 or better. If one assumes that the leaf area is proportional to the plant dry weight, one can further test the validity of equation (5) on the basis of yield data for early growth. This proportionality between leaf area and plant weight has been verified by regression analysis (correlation coefficient r of 0.90 and over, (57)(58)(59)(60)). Using this assumption, equation (5) was verified to hold for all the yield data available (references marked by an asterisk in the reference section): values of x are comprised between 1.5 and 3 and the regression correlation coefficient r was 0.95 or better in all cases for age stands

reaching up to 6 or 7 years. Equation (5) is thus well supported by experimental evidence.

The photosynthate produced yearly (equation (4)) will contribute to the growth of the various parts of the tree, and in particular to the above-ground biomass of interest in the Energy Plantation concept (8).

Thus $(dy_n/dn) \approx (d(PS)/dn)$ where y_n is the cumulated above-ground biomass at the age n . On the basis of equations (4) and (5) alone, biomass yields would tend to increase indefinitely with age. It is thus necessary to account for the fact that as age increases, more and more energy is required to maintain the existing living tissues, and thus a smaller fraction of the photosynthate contributes to actual plant growth. Keeping this in mind and combining equations (4) and (5), the following equation is proposed to describe above-ground biomass growth.

$$\frac{dy_n}{dn} = K n^x \left(1 - \frac{y_n}{y_{\max}}\right) \quad (6)$$

where y_n is the cumulated yield at age n , n is the age of the stand, $K = CA$ and x are constants specific to the species of interest and the growing conditions considered, and $y_{\max}$ is the maximum yield achievable by a plant grown under the field conditions imposed.

The factor $(1 - y_n/y_{\max})$ accounts for the energy required to maintain the existing living tissues during the period considered. Formally, equation (6) is identical to the growth rate equation used by Botkin, et al. (9). These authors, however, express leaf area as a function of stem basal area and use step-by-step integration to solve the growth rate area.

The solution of equation (6) for the cumulative yield at year n , y_n (o.d. lbs), of an individual tree growing under specified conditions (density of plantation, climate, etc.) is given by a function of the form

$$y_n = y_{\infty} [1 - e^{-(n/n_0)^m}] \quad (7)$$

where

y_{∞} = asymptotic yield, o.d. lbs

n_0 = characteristic age, years

m = number, empirically derived

n = age of tree, years

The function (7) is an S-shaped curve, the derivative of which is

$$\frac{dy}{dn} = \left(\frac{y_{\infty}}{n_0} \right) m \left(\frac{n}{n_0} \right)^{m-1} e^{-\left(\frac{n}{n_0} \right)^m} \quad (8)$$

which, using equation (7), may be rewritten as

$$\frac{dy}{dn} = \left(\frac{y_{\infty}}{n_0} \right) m \left(\frac{n}{n_0} \right)^{m-1} \left(1 - \frac{y}{y_{\infty}} \right) \quad (9)$$

The significance of the parameters y_{∞} , m and n_0 used in equation (7) is apparent when comparing equations (6) and (9). The quantity y_{∞} is equal to $y_{\max}$ in equation (6). It is the asymptotic yield reached by a tree growing under given conditions. For a given set of growing conditions (climate, treatment, etc.), the best candidates for Energy Plantations will be the species having the highest value of y_{∞} for the conditions considered.

The exponent m equals $x + 1$ (see equation (5) for the definition of x) and thus reflects the influence of the leaf area per tree on growth.

The quantity n_0 , which has the dimensions of a time, equals $(m y_\infty / K)^{1/m}$. It is such that at age n_0 , the tree will have reached about 63 percent of its maximum potential y_∞ for the growing conditions considered (equation (7)). A small value of n_0 thus ensures that the land is fully used in a short period of time. The parameter n_0 reflects the combined effects of leaf area through m , of the growth potential of the site through y_∞ , and of the specific rate of photosynthesis of the species considered through K .

The maximum rate of growth (equation (8)) is reached for

$$\left(\frac{n}{n_0}\right)_{\max} = \left(\frac{m-1}{m}\right)^{\frac{1}{m}} \quad (10)$$

Substituting n_0 as $(m y_\infty / K)^{1/m}$, it can be seen that the maximum growth rate is reached for

$$n_{\max} = \left[\left(\frac{y_\infty}{K}\right)(m-1)\right]^{\frac{1}{m}} \quad (11)$$

It is easily verified that, all other conditions being identical, $n_{\max}$ decreases when m increases; i.e., full occupancy of the land is expected at an earlier age for high-leaf-area species, for $(y_\infty / K) \gg 1$. This last condition is expected to be valid in all cases as y_∞ , the asymptotic yield for a tree, is measured in pounds per tree while K , the photosynthetic rate per unit leaf area, is generally measured in milligrams or grams per centimeter square per year (59,61). Similarly, the maximum growth rate can be expressed as

$$\left(\frac{dy}{dn}\right)_{\max} = y_{\infty} \cdot \left(\frac{K}{y_{\infty}}\right)^{\frac{1}{m}} (m-1)^{\frac{m-1}{m}} e^{-\left(\frac{m-1}{m}\right)} \quad (12)$$

by introducing expression (10) in equation (8) and substituting n_0 as $(m y_{\infty}/K)^{\frac{1}{m}}$. It is then easily verified that all other conditions being identical, the maximum rate of growth increases as the leaf area per tree as measured by m increases. Also, all other conditions being identical, as seen from equation (12), the maximum growth rate increases with K , the photosynthetic rate per leaf area and with y_{∞} , the asymptotic yield for the growing conditions selected. The yield-time function proposed (see equation (7)) thus accounts for the expected trends in plant growth resulting from changes in leaf area per tree, photosynthetic rate per unit leaf area and potential yield for given soil, climate and planting conditions.

The three quantities, y_{∞} , n_0 and m , used to describe plant growth, are functions of a number of factors such as species considered, growing conditions, cultural treatments, etc. The approach chosen here is to determine the values of y_{∞} , n_0 and m from existing experimental data for species of interest for plantation applications and then, when enough data are available, to establish functional relations between these parameters and factors under the control of the plantation operator, such as planting density and level of cultural treatment. Following Botkin et al. (9,55), climatic or soil quality effects are included in biomass yield estimates at a given site by multiplying the right-hand side of equation (7) by weighted factors characterizing the climatic and soil conditions of the site of interest in relation to some reference site. In the present case, the reference site is the site where the experimental data used to determine the parameters m , n_0 and y_{∞} were generated.

The individual tree-growth model proposed here has some features which make it useful for the purpose at hand, i.e., plantation optimization for highest energy yield and lowest cost:

a. The growth behavior of an individual tree is described in terms of three parameters y_{∞} , n_0 and m determined from experimental data. This approach is similar to that of Botkin, et al. (9,55), who rely on three experimental parameters (maximum diameter, maximum height and a growth constant) for their growth equation. It should be noted that these authors introduce a quantity defined as the product of maximum diameter by maximum height which has essentially the same significance as the parameter y_{∞} used in equation (7).

b. In principle, only three experimental points are necessary to determine the parameters needed to apply the growth model for a given set of growing conditions. Although the precision of the parameters determined on the basis of three points will be limited, this is an attractive feature in view of the limited data base available at present for fast-growing short-rotation plantings.

c. The model expresses yield directly as a function of age, as is the case for the model developed by Ek and Brodie (10,51), for instance, rather than through an age-related quantity such as the basal area (9).

d. As is discussed below, the growth parameters for individual trees, y_{∞} , n_0 and m , can be related to spacing between trees. This feature is also included in Ek's model (10). This author has stressed the importance of making the dependence of stand yield on planting density explicit when optimizing plantation yields (51).

The approach to tree-growth modeling chosen here is thus a pragmatic one which relies on the limited existing data. It is justified a posteriori by the fact that the error between the yields predicted from equation (7) and the observed experimental yields is, in general, less than 10 percent of the experimental values and often less than 5 percent.

B. Determination of the Growth Parameters

Experimental data on short-rotation high-density plantations usually report the cumulated yields of a given species as a function of age for a plot of given size and characteristics and for one or several planting densities. Complete data also include survival values as function of age.

Following equation (1), the yields are expressed as yields per tree, y_n (o.d. lbs/tree), using the reported values of N_n (or the survival rates).

A computer program was established to fit the experimental data by a function of the form

$$y_n = C_1 (1 - e^{-C_2 n^m}) \quad (13)$$

where C_1 = asymptotic yield = y_∞ of equation (7), o.d. lb/tree
 C_2 = limiting factor = n_0^{-m} (see equation (7)), years^{-m}
 m = number, empirically determined, reflecting leaf area development with age
 n = age, years

The program tries values of m equal to 1, 1.5, 2, 2.5, 3, 3.5 and 4. For each fit, the program calculates a χ^2 equal to

$$\chi^2 = \frac{1}{N - (\text{number of parameters} + 1)} \sum_{i=1}^N \frac{(y_i \text{ measured} - y_i \text{ calculated})^2}{\sigma_i^2} \quad (14)$$

where N = number of data points

σ_i^2 = square of standard deviation for y_i
 = 1 for unit weight distribution.

In the present case, $\sigma_i^2=1$, χ^2 cannot be used to estimate a level of confidence, but it can be used to determine which curve (or value of m) gives the best fit.

The actual values of the parameters m , C_1 , and C_2 depend on parameters characterizing the conditions of growth. Among these parameters, the area per plant at planting, $A(\text{ft}^2/\text{plant})$, is a dominant factor.

For most species of interest in this study, a single value of m may generally be used for the range of planting areas of interest (1 to 20 ft^2/tree). On the other hand, C_1 and C_2 or n_0^{-1} appear to depend significantly on A , all other conditions being constant. To optimize the design of the plantation, it is necessary to determine the functional dependence of C_1 and C_2 on A ; once such a dependence is established, it becomes possible to interpolate and/or extrapolate values of C_1 and C_2 for values of A within or outside of the range of values of A for which experimental data exist.

The procedure outlined above is used for both first and subsequent or coppice harvests.

C. Dependence of the Growth Parameters on Cultural Factors

The growth potential of a given area of land expressed, for instance, as pounds of biomass produced per acre per year is determined by local conditions such as availability of water and nutrients, length of the growing season, insolation, ambient temperature profile, etc. One of the problems facing the manager of an Energy Plantation is to choose the species and species management conditions which will produce an amount of biomass approaching as closely as possible the growth potential of the land area considered over as short a period of time as possible.

The parameters y_{∞} , n_0^{-1} and m which characterize the growth of individual trees depend on the same general conditions--water, nutrients, growing season, etc.--determining the overall growth potential but depend also on cultural treatments. Among the latter, the planting density or area per tree at planting $A(\text{ft}^2/\text{tree})$ has been found to be a dominant factor (3,4,5,13 to 32). In view of the major role and, particularly, its impact on the economic viability of the plantation, it is particularly important to elucidate the dependence of the growth parameters on A . This is the first objective of the present section. The influence of cultural and other factors, such as fertilization, cultivation, soil quality, etc., will also be briefly considered.

1. Dependence of the Limiting Factor n_0^{-1} on the Area per Tree at Planting, A

Before discussing the dependence of the growth parameters on A , the area per tree at planting, a remark should be made on the principle

of the approach. Indeed, while the growth characteristics in the first year are influenced by and probably related to the planting area, in the next year, the area per tree generally increases as tree survival is not 100 percent. Thus, referring growth parameters to the initial planting density for years over the first is not strictly valid. However, as was shown in Section IV, trees well-adapted to climate and soil conditions of the plantation and benefiting from appropriate cultural treatments (weed control, etc.) display survival rates of 90 percent or better in their first years of growth. Relating the growth parameters to the initial planting density thus introduces an error of principle of about 10 percent only, which is certainly within the limits of validity of any model of biological phenomena. Moreover, the yield data of individual trees as determined from the experimental data (see Section V.B) takes implicitly into account this variation of effective area per tree. Thus, as long as the survival rates and growth parameters expressed in terms of A used in the estimates of yields are matched, i.e., correspond to the same set of original data, the results will closely reflect reality.

It was found that a realistic representation of the dependence of n_0^{-1} on A (ft²/tree) was obtained through a function of the form

$$n_0^{-1} = \kappa A^\lambda \quad (15)$$

where κ and λ are constants evaluated from experimental data. As will be shown later, λ is generally negative, and as a result, the function (15) displays a decreasing slope as A increases, as would be expected.

The rationale for using an allometric equation (equation (15)) to describe the dependence of a biomass-dependent variable (n_0^{-1} in this case) on an independent, measurable variable (area per tree, A (ft²/tree) in this case) has been discussed in Section IV (see also reference 12).

Unfortunately, for the species of interest to the project, no complete set of data covering a wide enough range of values of A to determine precisely the functional dependence of n_0^{-1} on A was found for a given site. In the plant-growth model, the dependence of n_0^{-1} on A will thus be limited to small values of A , and the range of values of A over which the $n_0^{-1}(A)$ function is valid will have to be stated (up to about 25 ft²/tree in most cases).

The procedure outlined here is used both for first harvest and for coppice harvests.

Typical values of κ and λ for species of interest are shown in Table C-3.

A few comments can be made on the basis of these values:

a. In most cases, the values of κ and λ for coppice growth are significantly higher than those for first growth. This reflects the faster occupancy of the land during coppice growth as several shoots regrow from one stump; i.e., during coppice growth the plant appears more like a bush than a tree.

This planting-density-dependent effect of faster occupancy by coppice growth as compared to first growth was also noted by Bowersox and Ward (70) for hybrid poplar (clone NE-388).

b. For similar species, the values of κ and λ for first and coppice growth are generally very similar. This is demonstrated by the values

TABLE C-3

GROWTH PARAMETERS OF SOME SPECIES OF INTEREST FOR ENERGY PLANTATIONS

Species	First Growth						Coppice Growth					
	$m_1^{(1)}$	$K_1^{(2)}$	$\lambda_1^{(2)}$	$\alpha_1^{(3)}$	$\beta_1^{(3)}$	$\%^{(4)}$	$m_2^{(1)}$	$K_2^{(2)}$	$\lambda_2^{(2)}$	$\alpha_2^{(3)}$	$\beta_2^{(3)}$	$\%$
Populus Tristis	4	0.29095	-0.06927	2.1224	0.7430	6	4	0.8187	-0.4999	2.8725	0.7550	6
Hybrid Poplar NE388	2.5	0.2529	-0.06745	1.4302	0.8361	4	2.5	0.7116	-0.4869	1.9356	0.8496	4
Eastern Cottonwood	2	0.2040	-0.1745	3.711	0.9610	10	2	0.6390	-0.2688	3.710	0.9610	10
Sycamore	4	0.3434	-0.0283	2.4138	0.5716	8	3	0.3059	-0.0254	4.1022	0.5798	8
Eucalyptus	2	0.2109	-0.055	2.7472	0.90	4	2	0.6607	-0.1493	2.748	0.900	4

(1) Empirically determined exponent related to leaf area appearing in growth equation (7).

(2) Constants estimated from experimental data expressing the dependence of the characteristic age n_0 on the planting density $n_0^{-1} = KA^\lambda$.

(3) Constants estimated from experimental data expressing the dependence of the asymptotic yield y_∞ on the planting density A (ft²/tree) through $y_\infty = \alpha A^\beta$.

(4) Difference between calculated values from growth equation and experimental values expressed as percent of experimental values. Errors are for age 2 and higher.

Original data from references marked with asterisk in Reference Section.

for *Populus Tristis* and NE-388 in Table C-3 and reinforced by the κ and λ values estimated for other hybrid poplars (not reproduced in the table). This similarity in the κ and λ values for similar species suggests that a general relationship n_0^{-1} as a function of A can be determined for similar species. Such a general relationship for a group of species can then be used to determine the growth parameters of species within the group considered for which not enough experimental data are available to completely characterize the species considered. This point is further examined in Section D below.

2. Dependence of the Asymptotic Yield y_∞ on the Area per Tree at Planting, A

The reasoning developed about the parameter n_0^{-1} in Section 1 above applies similarly in the case of the asymptotic yield y_∞ . In the latter case, however, it is expected that y_∞ will increase as A increases. The constraints which were mentioned in the case of n_0^{-1} apply similarly in the present case, and it is thus suggested to represent the dependence of y_∞ on A by a function of the form

$$y_\infty = \alpha A^\beta \quad (16)$$

where α and β are constants determined from experimental data. Typical values of α and β for species of interest are shown in Table C-3.

Remarks similar to those made about the n_0^{-1} -versus-A dependence may be made about the y_∞ (A) function for various species; i.e., similar values of α and β are observed for groups of species having comparable growth characteristics. A general y_∞ (A) function can often be

obtained for groups of similar species which can be used to interpret limited sets of data (see Section D below).

It is interesting to note that the values of the exponent β in equation (16) are often close to 1 (see Table C-3, the most notable exception being sycamore). Thus the product of the asymptotic yield per tree, y_∞ , by the number of trees planted, N_0 ,

$$y_\infty \times N_0 \approx A^\beta N_0 \approx A^\beta A^{-1} \approx \text{independent of } A \quad (17)$$

which measures the overall productivity of the area of land considered, is essentially independent of the planting density as it should. Thus as noted earlier, the optimization procedure followed in choosing the planting density A and the corresponding growth parameters y_∞ , n_0^{-1} and m is a method by which the full growth potential of the land is achieved in the most economical way.

It is noteworthy that the dependence of yields on planting density as stated in the model of Ek and Brokie (10) for aspen is very similar to that expressed by the model used here.

3. Dependence of m on the Area per Tree at Planting A

The parameter m which appears as an exponent in the individual tree-growth equation (equation (7)) characterizes the leaf area development of the tree considered (see discussion of Section V.A). It is a species-specific quantity.

The data available do not suggest a systematic dependence of m on A . In most cases analyzed so far, a single value of m may generally be

used for the range of planting densities of interest. For a given species, however, different values of m may be used for first and coppice growth, as is apparent in Table C-3.

4. Biomass Estimates from the Plant-Growth Model

The growth parameters presented in Table C-3 were used to calculate biomass yields. As indicated in the table, the error between the calculated and experimental yields is generally less than 10 percent and often close to five percent of the experimental data for first growth. The case of first growth of hybrid poplar NE 388 is particularly significant as the parameters were derived from 15 experimental points (five years of growth and three replica (15)), and is indicative of the precision which can be achieved in predicting biomass yields from the simple model used (equation (7)).

The error between estimated and experimental yields is somewhat higher for coppice growth (5 to 10 percent generally) than for first growth. This is due to the fact that the data base for coppice growth is less extensive than for first growth, and as a result, the uncertainty on the growth parameters for coppice growth is higher than for first growth. The overall error expected on the estimated yields is of the order of 8 to 10 percent, which is within the range of variations in yield expected from seasonal climatic fluctuations.

5. Dependence of Growth Parameters on Cultural Factors Other Than the Planting Density

Independently of their dependence on the planting density, the values of the parameters y_{∞} and n_0^{-1} are also influenced by the cultural treatment applied to the plantation. The effect of weed control and

soil preparation and of fertilizer have been examined; the results of a number of studies are summarized below.

a. Site Preparation and Site Management

Various site preparation programs and site management programs have been compared for species such as sycamore (33,23), sweet gum (33,), cottonwood, Russian olive, blackberry and green ash (29). The data indicate that:

- site preparation before planting, including removal of plant material followed by disking, contributes to higher growth rates (higher values of y_{∞} and n_0^{-1}),
- weed control after planting and until the species is well established contributes significantly to the growth rate,
- disking appears to be the best method for weed control although the use of a cover crop may be another effective means (71 to 73).

b. Dependence of the Growth Parameters on Fertilization

Experiments with sycamore and black cottonwood (36,74,31,71) have shown that these species do respond to fertilization. This response will depend on the amount of fertilizer applied but also on the quality of the soil: the effect of fertilization on sycamore growth appears to decrease significantly as the site index for sycamore of the plantation land increases (23,33). The growth parameters describing tree growth do reflect the impact of fertilization: the value of the asymptotic yield y_{∞} increases while the value of n_0^{-1} decreases when fertilizer is used, which reflects higher yield potential and faster occupancy of the land. The available data are not sufficient at this time to include variations of the growth parameters as a function of fertilization.

D. Determination of the Growth Parameters from Limited Sets of Experimental Data

The determination of the growth parameters y_{∞} and n_0^{-1} require at least two, and preferably more, yield data points for a given planting area per tree A (see Section V.B above). In a number of cases ((29), for instance), valuable data on tree growth are only available for one year and one planting density. The general y_{∞} -versus-A curves (see Section V.C.2) can be used to obtain at least approximate growth parameters for these species.

The procedure involves using the y_{∞} (A) curves applicable for the species of interest to determine y_{∞} for the value of A used in the experimental plot(s). Having determined y_{∞} , n_0^{-1} can then be estimated from one experimental point. The best value of m is determined by trial and error. A detailed analysis of several cases indicates that this approximate method can reproduce experimental data within less than 10 percent, and often within less than 6 percent of the original values.

E. Nutrient Balance

Intensive biomass production on a short-rotation schedule, in the same way as agriculture, will require some form of fertilization to maintain productivity on a sustained basis. While optimization of fertilization for maximum yield was not included in this analysis (see Section 5,b above), a nutrient balance was performed to determine the amounts of nitrogen, calcium, potassium, magnesium and phosphorus required to maintain productivity under short-rotation harvesting conditions. The following steps were included in the analysis:

- 1) determination of the fractional weight composition of young trees as a function of age. For sycamore for instance, leaves represent about

sixteen percent of the total above-ground biomass weight at age two but only about nine percent by age four (75).

2) determination of the mineral composition of leaves, stem and branches for young trees. The data available for eastern cottonwood, sycamore and various poplar species show that the mineral composition of the tree parts are very similar for these species of interest for Energy Plantation applications (45,75,76,77,78,79).

3) evaluation of the amounts of nutrients removed per oven-dry ton of biomass harvested for various harvesting cycles (2 to 4 years). The results are shown in Table C-4. The first number of the range of nutrients quoted corresponds to the case of harvest without the leaves and the second number corresponds to the case when leaves are harvested. It should be noted that the numbers generated match closely the estimates of nutrient removal from wastewaters or sludge by deciduous forests as estimated by Sopper (80).

4) calculate the amounts of fertilizer required to replace the nutrients removed through harvesting the plantation. It is assumed that fertilizer is applied once at the beginning of each growth cycle--after harvest when the plantation is easily accessible by machinery. It is further assumed that one-fourth of the nutrients applied is lost through ground leaching and other mechanisms (81). The rates of application of fertilizer are then estimated for various rotation deviations and used in the plantation model to determine the amounts of fertilizer required to maintain the productivity of the plantation.

F. Characterization of Land Considered for Plantation Uses

Identification and characterization of land considered for plantation uses are based on information compiled by the Soil Conservation Service of the U.S. Department of Agriculture in the course of developing a national inventory of soil and water conservation needs (82). The inventory is based on field inspection and soil sampling in 1966 and 1967 throughout the forty-eight

TABLE C-4

MINERAL NUTRIENTS REMOVED WITH A BIOMASS HARVEST

Nutrient = Pounds Per Ton of Biomass (O.D. Basis) ⁽¹⁾					
<u>Rotation (Years)</u>	<u>N</u>	<u>Ca</u>	<u>K</u>	<u>Mg</u>	<u>P</u>
2	8.0-14.1	12.0-15.0	5.5-8.9	1.0-1.9	0.8-1.4
3	8.4-12.9	12.5-14.7	5.9-8.4	1.0-1.7	0.9-1.3
4	8.9-12.3	13.3-14.9	6.4-8.3	1.1-1.6	1.0-1.3

(1): Range of values of nutrients corresponds to harvest without leaves (dormant season, lowest value) and harvest with leaves (growing season, highest number).

contiguous states. Therefore, all the land estimated to be suitable for plantations is included in the inventory. The inventory is the most detailed available nationwide compilation of the topography, soil character and practical usefulness of land for producing plant material in managed operations.

1. Description of the National Inventory

The inventory was prepared for the guidance of those concerned with using rural land for cultivated crops, orchards and bush fruits, pasture, range, woodland, wildlife refuge, recreation and aesthetic purposes. Land is omitted from the inventory which in 1967 was owned by or under the control of the federal government (except cropland operated under lease from the government), was in urban or otherwise built-up areas such as industrial sites, was devoted to surface transportation or sporting activities (golf courses, for instance), was in institutional or publicly administered sites, or was occupied by water (lakes, reservoirs, ponds, and streambeds). Therefore, the inventory includes all the land which could be considered under any circumstances for Energy PlantationsTM. As an example of the area included in the inventory, the data for Louisiana are shown in Table C-5. The column headed "urban and built-up" includes all the land excluded from the inventory which is not included under the headings "Federal noncropland" and "small water area."

The land in the inventory has been divided into eight "land capability classifications." These classifications take account of soil and land forms in each county, and many counties are divided into several classifications. The descriptions of the classifications are summarized in Table C-6 and are more fully described in Reference 83. Land in classifications One through Four is suitable for cultivation by plowing, for instance, but as cropland it becomes less and less satisfactory as the classifications progress from One to Four. Land in classifications Five through Eight is not suitable for production of any plant material in managed operations. It is suitable only for wildlife refuges, recreation (with severe limitations), and aesthetic purposes.

TABLE C-5

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TABLE 1 LAND AREA, NON-INVENTORY AND INVENTORY ACREAGE - 1958 and 1967

STATE AND COUNTY	TOTAL LAND AREA 1957 ^{1/}	NON-INVENTORY ACREAGE								INVENTORY ACREAGE	
		FEDERAL NON CROPLAND		URBAN AND BUILT-UP		SMALL WATER AREA		TOTAL		1958	1967 ^{1/}
		1958	1967	1958	1967	1958	1967	1958	1967		
Acadia	423,852	0	0	16,746	17,245	1,901	2,849	18,647	20,095	405,033	403,757
Allen	495,000	0	0	15,288	15,485	6,330	6,350	21,618	21,858	474,382	475,132
Ascension	192,030	0	0	8,500	10,550	2,000	2,100	10,500	12,650	181,500	179,350
Assumption	222,242	0	0	4,500	4,615	7,100	7,100	11,600	11,715	216,890	210,527
Avoyelles	541,341	0	0	7,330	7,730	5,126	5,126	12,456	12,856	516,184	528,485
Beauregard	748,380	0	0	14,550	16,850	934	1,329	15,484	18,179	742,201	730,201
Bienville	523,379	0	0	20,575	21,465	1,477	1,593	22,072	23,058	503,943	500,321
Rossier	545,574	50,242	43,026	24,400 ^{2/}	7,764	4,000	1,192	78,642	56,982	458,078	488,592
Caddo	573,147	0	0	42,305	55,000	823	853	43,128	55,853	525,302	517,294
Calcasieu	692,616	2,380	0	38,350	44,586	4,053	10,987	44,828	55,573	661,732	637,043
Caldwell	350,590	0	28	5,978	6,500	5,071	5,000	11,049	11,528	340,951	339,062
Cameron	849,211	170,465	128,241 ^{3/}	5,803	8,593	30,901	31,401	207,169	168,635	716,991	680,576
Catahoula	463,240	0	0	8,225	8,740	7,800	7,605	16,025	16,345	450,947	446,895
Claiborne	481,944	18,533	17,125	15,575	17,290	1,310	1,550	35,410	35,965	454,822	445,979
Concordia	452,624	0	675	7,305	8,721	5,945	6,120	13,250	15,516	440,510	437,108
DeSoto	569,537	0	35	15,595	18,505	894	1,292	16,489	19,832	554,381	549,705
E. Baton Rouge	294,353	0	10	68,000	84,158	2,400	2,049	70,400	85,227	225,280	208,136
E. Carroll	275,840	0	0	4,000	4,264	1,277	1,322	5,277	5,592	270,703	270,222
E. Feliciana	290,051	0	0	6,210	16,276	2,240	2,019	8,450	18,295	282,110	271,756
Evangeline	427,325	0	0	8,829	10,100	2,331	2,400	11,160	12,500	417,750	414,825
Franklin	410,150	0	0	12,703	13,593	5,230	5,980	17,933	19,033	393,687	391,117
Grant	413,784	140,760	139,140	4,915	4,915	1,400	1,100	147,076	145,156	276,374	268,628
Iberia	377,654	5,525	5,525	10,651	11,245	11,290	11,290	27,466	28,064	348,054	349,590
Iberville	401,920	555	395	8,475	8,575	7,778	7,778	16,808	16,748	385,112	385,172
Jackson	371,912	0	0	4,524	4,524	329	329	4,853	4,853	368,222	367,059
Jefferson	231,860	0	0	46,872	70,000	15,000	15,000	62,872	85,000	198,888	145,860
Jefferson Davis	421,120	0	0	12,409	13,338	3,557	2,673	15,946	16,011	405,174	405,109
Lafayette	181,120	0	0	14,505	15,209	833	925	15,338	16,125	165,782	164,995
Lafourche	739,735	0	0	7,402	10,568	42,799 ^{4/}	4,200	50,201	24,768	690,279	715,017
LaSalle	407,620	0	5,318	16,350	7,924	1,515	1,003	17,865	14,225	390,455	393,395
Lincoln	292,731	0	0	14,427	20,919	1,070	1,280	15,497	22,199	284,605	277,532
Livingston	425,600	0	0	12,000	13,041	4,000	3,374	16,000	16,415	409,600	409,185
Madison	411,520	0	0	5,362	5,512	2,512	2,544	7,874	8,056	415,806	403,464
Morehouse	510,723	0	0	5,400	5,922	8,900	7,115	14,300	13,007	498,260	497,656
Natchitoches	812,985	131,537	126,881	15,225	15,625	2,035	2,260	148,857	144,766	678,623	668,119
Orleans	127,360	1,818	2,000	61,700	71,000	7,500	7,000	71,018	80,000	56,342	47,360
Ouachita	403,819	0	0	43,832	57,951	8,980	3,375	52,812	66,326	355,468	337,493
Flaquemines	630,160	48,929	48,929	9,082	9,000	57,188	57,000	115,199	114,929	514,561	515,231
Point Coupee	360,960	0	0	7,299	7,400	19,331	19,331	26,630	26,731	334,330	334,229
Rapides	858,069	113,854	103,923	37,103	33,162	4,919	5,019	155,882	147,104	691,042	710,965
Red River	253,037	0	0	5,126	6,725	1,020	1,210	6,146	7,935	258,174	245,102
Richland	358,550	0	0	6,649	6,849	7,203	7,243	13,852	14,092	354,788	354,458
Sabine	565,284	10,496	10,496	10,653	10,795	1,835	1,810	22,984	23,102	635,576	542,182
St. Bernard	326,400	6,513	7,000	9,218	12,000	30,195	30,000	45,926	49,000	280,474	277,400
St. Charles	193,302	0	0	6,500	7,000	9,990	10,000	16,490	17,000	178,070	176,302
St. Helena	268,800	0	0	1,350	2,550	1,050	1,300	2,400	3,850	266,400	264,950
St. James	159,350	0	0	2,613	3,803	816	860	3,429	4,663	155,931	154,697
St. John	144,030	0	0	2,868	4,000	2,775	3,000	5,643	7,000	138,357	137,000
St. Landry	594,600	0	0	22,800	25,800	12,200	12,400	35,000	38,200	560,200	555,400
St. Martin	493,394	0	0	4,827	4,827	7,737	7,737	12,564	12,564	448,876	470,740
St. Mary	407,345	0	64	8,253	15,242	20,537	20,827	28,850	36,191	353,350	371,154
St. Tammany	562,749	1,705	1,385	22,100	25,100	12,000	12,232	35,805	38,717	545,315	524,032
Tangipahoa	513,920	0	0	15,418	19,796	7,700	7,700	23,118	27,496	490,802	485,424
Tensas	398,720	0	0	5,438	6,074	5,128	5,085	10,566	12,159	383,154	385,561
Terrebonne	890,240	117	117	9,059	12,717	60,803	60,196	69,979	73,030	820,261	817,210
Union	564,269	0	0	13,416	15,264	2,339	2,570	15,755	17,834	564,085	546,435
Vermillion	783,350	0	0	16,578	18,235	18,437	18,855	35,065	37,091	748,295	746,269
Vernon	863,550	166,774	182,112	17,373	18,579	1,632	1,003	185,785	202,494	682,015	661,056
Washington	425,600	0	0	4,640	5,140	5,760	5,000	10,400	11,220	415,200	414,380
Webster	392,970	33,125	32,135	21,000	24,500	6,500	5,779	60,625	63,814	336,840	329,156
W. Baton Rouge	128,640	0	0	7,042	8,000	642	1,020	7,684	9,020	120,316	119,620
W. Carroll	227,840	0	0	7,421	7,650	1,457	1,500	8,878	9,150	218,962	218,690
West Feliciana	262,200	0	160	2,000	2,450	3,322	3,525	5,322	6,135	257,078	256,055
Winn	607,700	110,595	110,579	11,447	11,600	313	350	122,355	122,279	485,245	484,721

State Totals: 23,508,208 1,213,973 370,437 922,115 1,080,000 512,422 400,000 2,423,723 2,536,041 26,404,004 25,067,227

^{1/} Each parish was remeasured in 1966 to determine more accurate land areas and inventory acreages. The 1958 data did not fully reflect changes in boundaries, new reservoirs, alluvial depositions and lakes drained since 1940.^{2/} Believed to include Barksdale Air Force Base which had already been deducted as Federal land.^{3/} Does not include 42,334 acres previously deducted as large water acreage.^{4/} Believed to include many lakes in the marsh slightly over 40 acres in size and previously deducted as large water.

The land in the inventory is also classified according to the actual use to which it was devoted in 1967. Four broad-use categories, each having a number of subuses, are recognized, namely: cropland in tillage rotation, which also includes orchards, vineyards and bush fruits; pasture and range; forest; and other land.

The land capability classification and use of the land in 1967 in the inventory for one parish in Louisiana are shown in Table C-7. The data shown in the tables are abstracted from Reference 82.

It shows that land eminently suitable for field crops was being used for other purposes in that year (see Natchitoches parish, Capability Class One being used for pasture, for instance).

The land capability classifications Two through Eight are further subdivided into four subclassifications which describe the main limitations to the use of land for particular purposes. The subclassifications reflect the risk of erosion unless a good plant cover is maintained on the land, the likelihood of water on or in or not in the soil interfering with plant growth, the shallowness, stoniness or droughtiness of the topsoil, and climate limitations on the productivity of the land (usually too cold or too dry). These subclassifications are designated by the letters E (erosion), W (water), S (soil) or C (climate) following the classification numeral. The climate limitation is not applicable to any of the land which has been judged to be suitable for Energy PlantationsTM. Since land in Capability Class One has no severe use limitations, the designation One is never followed by a letter.

In assigning land to a particular capability classification, the land was ranked first on a scale of eight according to each of the four subclassifications. The higher the assigned number on the scale of eight, the more severe the subclassification limitation is to the use of the land. In a particular instance, a tract might have been assigned Six with respect to one of the subclassifications, and Five or better with respect to the other three.

TABLE C -6

SUMMARY DESCRIPTION OF THE LAND CAPABILITY CLASSIFICATIONS

<u>Classification</u>	<u>Description</u>
1	The land is almost level, soils are deep, easily worked, well drained, hold water well for crop production, and are responsive to fertilizer. There is little erosion hazard when plowed. The land is the most suitable for row (corn, for instance) and close-grown (wheat, for instance) crops. This land generally is accorded the highest value in its locality. This land would be ideal for Plantations, but because of its high value for other uses, little of it is likely to be offered for plantations.
2	The land may be gently sloping (up to about 6 percent grade), and may require contour plowing or some other measure to prevent wind and water erosion when it is cultivated. It may have less than ideal soil depth for annual crops and is usually less easily worked than soils in the first classification. It may suffer from wetness which, however, can be corrected by suitable drainage. It is a cut below prime dirt-farming land, a fact reflected in the value accorded it. The opportunity for using much of this land for plantations is believed to be about the same as for land in Classification One.
3	The land is often moderately sloping (up to about a 12 percent grade) and subject to rather severe wind and water erosion when cultivated unless extensive contour plowing is practiced. It may not be well drained and may have a shallow topsoil layer over a relatively hard subsoil structure which limits its productivity for annual crops. Its topsoil may have low moisture-holding capacity and its workability may not be very good. For dirt farming, it is of marginal value. Most of this land would be suitable for Plantations, but much of it may be too highly valued for that purpose.
4	The land may have slopes up to 18 percent, be very subject to erosion if plowed, and often has a shallow topsoil layer. Water-logging may be a problem. Crops requiring cultivation are not recommended, but orchards, vineyards, bush fruits, ornamental trees or shrubs may grow well. Much of this land will be well-suited to Plantations.

TABLE C-6 (continued)

SUMMARY DESCRIPTION OF THE LAND CAPABILITY CLASSIFICATIONS

<u>Classification</u>	<u>Description</u>
5	The land is usually nearly level, often wet and frequently flooded at certain times of the year. The land is not satisfactory for plowing and the soil is frequently stony. Using the land for woodland is sometimes acceptable, but it is best used for pasture and range. This land is not considered to be suitable for plantations.
6	The land may have slopes as steep as 25 percent and is unsuitable for plowing. However, the soil often responds to fertilization and is suitable for woodlands, improved pasture and range. The topsoil may be stony and shallow. Much of this land will be well suited to Plantations.
7	Slopes as steep as 35 percent may be found on this land. It is totally unsuited for cultivation, generally has stony and relatively shallow topsoil. It is best suited to woodland and range. Some of this land is believed to be suitable for plantations.
8	The land is unsuited to commercial plant production. It often has slopes steeper than 35 percent, is stony or even rocky and often is poorly drained. The topsoil layer is thin. None of this land is considered suitable for plantations.

TABLE C-7

LAND CAPABILITY CLASSIFICATION OF A PARISH IN LOUISIANA AND USE OF THE LAND IN 1967

Land Capability Class Subclass	Cropland in Tillage Rotation										
	Field Crops				Hayland	Conservation Use Only	Temporarily Idle Cropland	Total Tillage Rotation	Orchards Vineyards and Bush Fruit	Open Land Formerly Cropped	Cropland
	All Row Crops	Close- Grown Crops	Total Field Crops	Rotation Hay and Pasture							
1	11200	700	11900	100		1000		13000	2000		15000
2W	16600	200	16800			2200		19000	3300		22000
3W	3000	100	3100			7000		10100	10000		20100
TOTAL	30800	1000	31800	100		10200		42100			57100

TABLE C-7 (Continued)

LAND CAPABILITY CLASSIFICATIONS OF A PARISH IN LOUISIANA AND USE OF THE LAND IN 1967

Land Capability Class Subclass	<u>Pasture-Range</u>			<u>Forest</u>						<u>Other Land</u>			<u>Total Land in Inventory</u>
	<u>Pasture</u>	<u>Range</u>	<u>Total</u>	<u>Com- mercial</u>	<u>Noncom- mercial</u>	<u>Total</u>	<u>Commercial Grazed</u>	<u>Noncom- mercial Grazed</u>	<u>Total Grazed</u>	<u>In Farms</u>	<u>Not In Farms</u>	<u>Total</u>	
Natchitoches Parish													
1	9589		9589	4325		4324	4325		4325	1372		1372	30286
2E	5163		5163	23199		23199	23199		23199		343	343	28705
3E	2949		2949	75102		75102	75102		75102	1333	2097	3430	81481
4E	4425		4425	73529		73529	73529		73529	753	962	1715	79669
6E	7376		7376	115995		115995	115995		115995	342		342	123713
2W	16225		16225	7078		7078	7078		7078				45303
3W	90715		90715	85718		85718	85718		85718				196533
4W				3539		3539	3539		3539				3539
5W	14013		14013	51510		51510	51510		51510				65523
2S				3538		3538	3538		3538				3538
3S				8650		8650	8650		8650				8650
4S				1179		1179	1179		1179				1179
TOTAL	150455		150455	453362		453362	453362		453362	3800	3402	7202	668119

Under such circumstances, the land is assigned to capability classification Six with the letter designation of the subclassification which established the capability class appended after the Six. For instance, land classified as 4E means that the most severe limitation to its use is erosion if it does not have a good ground cover of plants to protect it from wind or flowing water. The level four means that the erosion risk is intermediate in the range from no substantial risk (Classification 1) to very severe risk (Classification 8). Classification 4 also means that the land should not be plowed unless elaborate precautions, such as contour plowing, are taken to prevent erosion.

In the event that a tract was ranked equally with respect to two or more subclassifications, but not as severely with respect to the others or other, the tie was broken by considering erosion susceptibility to be a more stringent limitation on the use of the land than water problems, which in turn were considered more restricting than limitations arising from soil character. Thus, if the tie was between erosion susceptibility and wetness, the code letter for the former (E) is included with the rank number.

2. Productivity Weighting Factor of Plantation Land

The land available for plantation use will generally be made of parcels of various land capability classes. In the absence of a detailed description of the area available for the plantation, an average weighted land class (AWLC) is defined through

$$(AWCL) = \frac{\sum_i (LA)_i \times (PI)_i}{\sum_i (LA)_i} \quad i = 1 \text{ to } 7 \quad (13)$$

where $(LA)_i$ = land area of class i available for plantation use (acres).
Land of Class 8 is not included in the summation as it is generally unsuited for plantation (slopes, rocks, etc).

(PI)_i = productivity index of the land of class i as defined in Reference 84. These productivity indexes give the relative value of the yield expected from land of various classes submitted to the same cultural practices. Table C-8 below gives the land classes and their associated productivity indexes.

For example, land Not in Farms in Table C-7 would have an average weighted land class of

$$(AWLC) = \frac{343 \times 1.35 + 2097 \times 1.00 + 962 \times 0.75}{3402} = 0.96 \quad (14)$$

thus this mix of land areas will display a productivity equal to 96 percent of that of land of Class 3 taken as a basis of comparison.

TABLE C.- 8

PRODUCTIVITY INDICES AS FUNCTION OF LAND CLASS (FROM REFERENCE 84)

<u>Land Class</u>	<u>Productivity Index</u>
1	1.50
2	1.35
3	1.00
4	0.75
5	0.50
6	0.35
7	0.15
8	0.10

Excluding land Class 8, the data of Table C-8 can be represented by

$$(PI) = 1.7357 - 0.2339 (LAND) \quad (15)$$

where (PI) = productivity index
(LAND)= land class.

Equation(15) is a good representation of the data of Table C-8 for land Classes 2 to 6 which are of most interest for plantation applications (correlation coefficient $r = 0.99$).

Using data relating tree yields to land quality measured by site indexes, (23, 30, 25), it was shown that plantation productivity follows closely the productivity index scale of equation (15) for land of various classes. It was thus decided to weight the productivity predicted by the plant-growth model (see Section V) on the basis of the productivity indexes discussed here.

The problem addressed here is the following: the tree growth data used to determine the plant growth parameters y_{∞} and n_0^{-1} were generated on experimental plots of a certain land class or a certain productivity index. The productivity index of the land on which the original experimental data was generated (PIS) is estimated on the basis of equation (15) and is included in the data bank for each species considered.

The yield predictions given by the plant-growth model are thus valid for land of this class or of index (PIS). When land of a different class is used in the plantation (as is generally the case), the predicted yields are then multiplied by the factor (AWLC)/(PIS) to take into account the difference in productivities between the plantation and the original experimental land.

G. Energy Efficiency of the Plantation.

The energy efficiency of the plantation η is defined as

$$\eta = \frac{E_{\text{out}} - E_{\text{in}}}{E_{\text{out}}} \quad (16)$$

where E_{out} = yearly energy output from the plantation (Btu/year)

E_{in} = yearly energy input to operate the plantation (Btu/year)

The energy output is estimated on the basis of the gross heating value of the wood chips produced (8,500 Btu/o.d. lb) and the annual sustained yield of the plantation (ASY) as estimated by the plantation model.

As discussed by Blankenhorn, et al. (85), fertilizers and fuels account for about 67 and 32 percent, respectively, of the total yearly energy input to operate a plantation if one excludes the energy required for manufacturing of the equipment. Following the PEF concept, a significant fraction of the potassium, calcium and phosphorus required by the plantation is obtained by recycling of the ash from the power plant boiler and of the sludge from the digester. Although some nitrogen is supplied by recycling the sludge, nitrogen is the major nutrient which has to be supplied from outside source to supplement the amount recycled. The energy input was thus estimated on the basis of the energy required to produce the supplemental nitrogen (in the form of ammonium nitrate, about 10,000 Btu/lb, (86,87)) and the energy value of the fuels used to operate the plantation machinery.

The energy efficiency estimated through equation (16) on this basis is generally of the order of 97 percent; i.e., the energy required to produce

the biomass is only about 3 percent of the fuel value of the biomass. For a 10-year rotation plantation, Blankenhorn, et al. (85) estimate an energy efficiency, as defined above, of about 5 percent; in the case considered by these authors, however, all the nutrients are supplied from outside sources.

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APPENDIX D

DETAILS OF POWER PLANT MODEL

Introduction

The power plant model simulates the performance of a power plant that accepts any fuel composed primarily of carbon, hydrogen, oxygen, nitrogen and ash. Capital and operating costs and the cost per unit of electricity output can also be calculated, provided that the coefficients needed in the capital cost equations are known for the corresponding fuel. Thus, for example, the model was used to compare electricity costs from coal-fired power plants to those from wood-fired power plants.

The primary purpose of the model is to predict the performance and electricity costs of a power plant that accepts solid fuel from an Energy PlantationTM. The composition, rate, and cost of Energy PlantationTM fuel are furnished from the Energy PlantationTM model. The power plant model in turn provides information needed for the algae pond model, consisting primarily of the temperature of the cooling water leaving the condenser, and the amount, temperature, and composition of the exhaust gas.

The model is constructed as a series of subroutines, each subroutine roughly corresponding to one element of the power plant configuration. A flow chart of the computer program showing the order in which the subroutines are used is shown in Figure D-1. Following is a detailed description of each subroutine stating its general purpose and listing all of its input and output parameters and the equations used to calculate the value of each output parameter.

This subroutine calls all input data for the power plant model, and where necessary converts values to the proper units needed for the calculations.

FIGURE D-1

FLOW CHART OF COMPUTER PROGRAM

PRELIMINARY CALCULATIONS (SUBROUTINE PRELIMIN)

The preliminary calculations calculate additional values needed as input for the other subroutines, and the energy loss rate due to unburned fuel removed by the screening process.

INPUTS

- ω_c - mass fraction of carbon in oven-dry fuel
- ω_{H2} - mass fraction of hydrogen in oven-dry fuel
- ω_{O2} - mass fraction of oxygen in oven-dry fuel
- ω_a - mass fraction of ash in oven-dry fuel
- ω_{wf} - mass fraction of water in as-delivered fuel
(wet-basis moisture content)
- ω_d - mass fraction of dirt in as-delivered fuel
- ω_r - ratio of rate of dried fuel removed by
screening process to rate of fuel delivered
to power plant.
- ω_{wb} - wet-basis moisture content of fuel and
dirt leaving dryer.
- F_f - rate at which fuel is delivered to power plant
- ΔH_h - higher heating value of oven-dry fuel

OUTPUTS

- ω_N - mass fraction of nitrogen in oven-dry fuel
- ω_{odf} - mass fraction of oven-dry fuel in as-delivered fuel
- F_{odf} - rate at which oven-dry fuel is delivered to power plant
- F_{wf} - rate at which water in fuel is supplied to power plant
- F_d - rate at which dirt in fuel is supplied to power plant
- F_{uf} - rate at which dried fuel is removed by screening process
- F_{odfb} - rate at which oven-dry fuel is supplied to boiler
- F_{wb} - rate at which water in fuel is supplied to boiler
- L_{uf} - energy loss rate due to unburned fuel removed by
screening process

EQUATIONS

$$\begin{aligned}\omega_{N2} &= 1 - \omega_c - \omega_{H2} - \omega_{O2} - \omega_a \\ \omega_{odf} &= 1 - \omega_{wf} - \omega_d \\ F_{odf} &= \omega_{odf} F_f \\ F_{wf} &= \omega_{wf} F_f \\ F_d &= \omega_d F_f \\ F_{uf} &= \omega_r F_f \\ F_{odfb} &= [\omega_{odf} - \omega_r(1 - \omega_{wb})] F_f \\ F_{wb} &= [\omega_{wb} / (1 - \omega_{wb})] \omega_{odf} F_f \\ L_{uf} &= \Delta H_h \omega_r (1 - \omega_{wb}) F_f\end{aligned}$$

BOILER CALCULATIONS (SUBROUTINE BOILER)

These calculations determine the properties of the various flows into and out of the boiler and the energy loss rates that are independent of the air preheater performance.

INPUTS

- ΔH_h - higher heating value of oven-dry fuel
- F_{odfb} - rate at which oven-dry fuel is supplied to boiler
- F_{wb} - rate at which water in fuel is supplied to boiler
- ω_c - mass fraction of carbon in oven-dry fuel
- ω_{cu} - ratio of rate of carbon removed unburned from boiler to rate of oven-dry fuel supplied to boiler
- ω_{H2} - mass fraction of hydrogen in oven-dry fuel
- ω_{O2} - mass fraction of oxygen in oven-dry fuel
- ω_{N2} - mass fraction of nitrogen in oven-dry fuel
- A_e - excess air supplied for combustion
- W - specific humidity of ambient air
- T_{amb} - temperature of ambient air
- C_{pCO2} - specific heat of carbon dioxide
- C_{pO2} - specific heat of oxygen
- C_{pH2} - specific heat of nitrogen
- C_{pvap} - specific heat of water vapor
- R_1 - fraction of energy input to boiler dissipated by radiation and unaccounted-for phenomena

OUTPUTS

- E_b - rate at which energy is released by combustion in boiler
- F_{CO2} - flow rate of carbon dioxide in flue gas
- F_{O2} - flow rate of oxygen in flue gas
- F_{N2} - flow rate of nitrogen in flue gas
- F_{dfg} - flow rate of dry flue gas
- F_a - flow rate of air supplied for combustion
- F_v - flow rate of water vapor in flue gas
- F_g - flow rate of flue gas
- h_{fgamb} - enthalpy of vaporization of water at ambient air temperature
- L_{H2} - energy loss rate due to evaporation of H_2O formed by combustion of hydrogen in fuel (latent loss due to hydrogen in fuel)
- L_w - energy loss rate due to evaporation of water in fuel (latent loss due to water in fuel)
- L_{cu} - energy loss rate due to carbon that does not burn (unburned carbon loss)
- L_{rad} - energy loss rate due to radiation and unaccounted-for losses
- H_{fg} - heat capacity rate of flue gas stream

EQUATIONS

$$\begin{aligned}E_b &= \Delta H_h F_{odfb} \\F_{CO2} &= 3.667 (\omega_c - \omega_{cu}) F_{odfb} \\F_{O2} &= [A_e (8\omega_{H2} + 2.667 \omega_c - \omega_{O2}) + 2.667 \omega_{cu}] F_{odfb} \\F_{N2} &= [\omega_{N2} + 3.31 (1+A_e) (8\omega_{H2} + 2.667 \omega_c - \omega_{O2})] F_{odfb} \\F_{dfg} &= F_{CO2} + F_{O2} + F_{N2} \\F_a &= 4.31 (1+W) (1+A_e) (8\omega_{H2} + 2.667 \omega_c - \omega_{O2}) F_{odfb} \\F_v &= [9\omega_{H2} + 4.31W (1+A_e) (8\omega_{H2} + 2.667 \omega_c - \omega_{O2})] F_{odfb} + F_{wb} \\F_g &= F_{dfg} + F_v\end{aligned}$$

$$\begin{aligned}
h_{fgamb} &= (1094.912 \text{ Btu/lbm}) - (0.5800906 \text{ Btu/lbm}^\circ\text{F}) T_{amb} \\
L_{H2} &= h_{fgamb} (F_v - F_{wb}) \\
L_w &= h_{fgamb} F_{wb} \\
L_{cu} &= \Delta H_h \omega_{cu} F_{odf} \\
L_{rad} &= R_l E_{in} \\
H_{fg} &= C_{pCO2} F_{CO2} + C_{pO2} F_{O2} + C_{pN2} F_{N2} + C_{pvap} F_v
\end{aligned}$$

DRYER CALCULATIONS (SUBROUTINE DRYER)

These calculations determine the evaporation rate in the dryer, the minimum temperature at which the flue gas can enter the dryer, the composition, flow rate and wet-bulb temperature of the dryer exhaust gases and the drying energy transfer rate.

INPUTS

F_f - rate at which fuel is delivered to dryer
 F_d - rate at which dirt in fuel is delivered to dryer
 F_{odf} - rate at which oven-dry fuel is delivered to dryer
 F_{wf} - rate at which water in fuel is delivered to dryer
 F_{CO2} - flow rate of carbon dioxide in flue gas entering dryer
 F_{O2} - flow rate of oxygen in flue gas entering dryer
 F_{N2} - flow rate of nitrogen in flue gas entering dryer
 F_v - flow rate of water vapor in flue gas entering dryer
 F_g - flow rate of flue gas entering dryer
 F_{uf} - rate at which dried fuel is removed by screening process
 C_{podf} specific heat of oven-dry fuel
 C_{pw} specific heat (liquid) water
 C_{pvap} specific heat of water vapor
 h_{fgamb} enthalpy of vaporization of water at ambient air temperature
 H_{fg} heat capacity rate of flue gas entering dryer
 T_{eg} (dry bulb) temperature of exhaust gas leaving dryer

- T_{amb} - temperature of ambient air
- ω_{wf} - wet-basis moisture content of fuel delivered to dryer
- ω_{wb} - wet-basis moisture content of fuel leaving dryer
- M_{CO_2} - molecular weight of carbon dioxide
- M_{O_2} - molecular weight of oxygen
- M_{N_2} - molecular weight of nitrogen

OUTPUTS

- D_r - rate at which water is evaporated from fuel in dryer (drying rate)
- H_f - heat capacity rate of dried fuel (including dirt) leaving dryer
- X_v - mole fraction of water vapor in dryer exhaust gas
- T_{wb} - wet-bulb temperature of exhaust gas (and temperature of dried fuel) leaving dryer
- F_{odaux} - flow rate of oven-dry fuel leaving screener and entering auxiliary burner and dryer
- H_{aux} - heat capacity rate of combustion products and dirt in auxiliary burner and dryer
- E_{aux} - rate at which energy is released by combustion in auxiliary burner and dryer
- L_{aux} - rate at which energy is lost as sensible heat to combustion products and dirt in auxiliary burner and dryer
- T_{fg} - temperature of flue gas entering dryer (leaving air preheater)
- F_{de} - flow rate of dry gas in dryer exhaust gas (dry exhaust gas)
- F_e - flow rate of dryer exhaust gas
- M_{de} - molecular weight of dry exhaust gas
- X_{CO_2} - mole fraction of carbon dioxide in dry exhaust gas
- X_{O_2} - mole fraction of oxygen in dry exhaust gas
- X_{N_2} - mole fraction of nitrogen in dry exhaust gas
- Q_d - rate of energy needed to evaporate water from the fuel

EQUATIONS

$$\begin{aligned}
 D_r &= [(\omega_{wf} - \omega_{wb}) / (1 - \omega_{wb})] F_f \\
 H_f &= (F_{wf} - D_r) C_{pw} + (F_d + F_{odf}) C_{podf} \\
 X_v &= (F_v + D_r) / (F_g + D_r) \\
 T_{wb} &= [(-9394.238^\circ R) / \ln(X_v / 1235950)] \\
 F_{odaux} &= F_{uf} (1 - \omega_{wf}) \\
 H_{aux} &= [F_{odaux} H_{fg} / F_{odf}] + F_d [C_{podf} + C_{pw} \omega_{wf} / (1 - \omega_{wf})] \\
 E_{aux} &= \Delta H_h F_{odaux} \\
 L_{aux} &= H_{aux} (T_{eg} - T_{amb}) \\
 T_{fg} &= \begin{cases} \max \left\{ \begin{array}{l} T_{eg} + \{ (T_{wb} - T_{amb}) H_f + [h_{fgamb} + C_{pvap} (T_{eg} - T_{amb})] D_r \} / H_{fg} \\ T_{eg} \end{array} \right\} & D_r > 0 \\ T_{eg} & D_r = 0 \end{cases} \\
 F_{de} &= F_{CO2} + F_{O2} + F_{N2} \\
 F_e &= F_{de} + F_v + D_r \\
 M_{de} &= F_{de} / (F_{CO2} / M_{CO2} + F_{O2} / M_{O2} + F_{N2} / M_{N2}) \\
 X_{CO2} &= M_{de} F_{CO2} / M_{CO2} F_{de} \\
 X_{O2} &= M_{de} F_{O2} / M_{O2} F_{de} \\
 X_{N2} &= M_{de} F_{N2} / M_{N2} F_{de} \\
 Q_d &= h_{fgamb} D_r
 \end{aligned}$$

AIR PREHEATER CALCULATIONS (SUBROUTINE ARHEAT)

These calculations determine the temperature of the air leaving the air preheater and the overall heat-transfer coefficient-area product of the air preheater.

INPUTS

C_{pda} - specific heat of dry air
 C_{pvap} - specific heat of water vapor

W - specific humidity of ambient air
 F_a - flow rate of air supplied for combustion
 H_{fg} - heat capacity rate of flue gas stream
 T_{fb} - temperature of flue gas entering air preheater
 (leaving boiler)
 T_{fg} - temperature of flue gas leaving air preheater
 (entering dryer)
 T_{amb} - temperature of ambient air (entering air preheater)
 D_r - rate at which water is evaporated from fuel in
 dryer
 h_{fgamb} - enthalpy of vaporization of water at ambient
 air temperature
 H_f - heat capacity rate of dried fuel (including dirt)
 leaving dryer
 T_{wb} - wet-bulb temperature of exhaust gases (and temperature
 of dried fuel) leaving dryer

OUTPUTS

H_{air} - heat capacity rate of combustion air stream
 Q_a - rate of heat transfer from flue gas to air in
 air preheater
 T_{ab} - temperature of air leaving air preheater (entering
 boiler)
 UA_a - overall heat-transfer coefficient-area product of
 air preheater
 T_{fg}^* - temperature of flue gas leaving air preheater
 (entering dryer)
 T_{eg}^* - temperature of exhaust gas leaving dryer

*These values are recalculated only when the temperature of the air leaving the air preheater would otherwise be greater than 10°F less than the temperature of the flue gas entering the air preheater.

EQUATIONS

$$H_{air} = F_a (C_{pda} + C_{pvap}) / (1+W)$$

$$Q_a = \begin{cases} H_{fg}(T_{fb} - T_{fg}) & \text{if } [T_{amb} + H_{fg}(T_{fb} - T_{fg})/H_{air}] \leq [T_{fb} - 10^\circ\text{F}] \\ H_{air}(T_{fb} - T_{amb} - 10^\circ\text{F}) & \text{if } [T_{amb} + H_{fg}(T_{fb} - T_{fg})/H_{air}] > [T_{fb} - 10^\circ\text{F}] \end{cases}$$

$$T_{ab} = \min \left(\begin{array}{l} T_{amb} + H_{fg}(T_{fb} - T_{fg})/H_{air} \\ T_{fb} - 10^\circ\text{F} \end{array} \right)$$

* If $[T_{amb} + H_{fg}(T_{fb} - T_{fg})/H_{air}] > [T_{fb} - 10^\circ\text{F}]$, T_{fg} and

T_{eg} are recalculated according to

$$T_{fg} = T_{ab} - Q_a/H_{fg}$$

$$T_{eg} = H_{fg}T_{fg} - D_r(h_{fgamb} - C_{pvap}T_{amb}) - H_f(T_{wb} - T_{amb}) + E_{aux} + H_{aux}T_{amb} / (H_{fg} + H_{aux} + C_{pvap}D_r)$$

$$UA_a = Q_a \ln([T_{fb} - T_{ab}]/[T_{fg} - T_{amb}]) / [(T_{fb} - T_{ab}) - (T_{fg} - T_{amb})]$$

RANKINE CYCLE CALCULATIONS (SUBROUTINE RANKIN)

These calculations determine the steam conditions and energy transfer rates throughout the Rankine power cycle, the energy loss rate in the boiler due to the higher-than-ambient temperature of the combination products, the flame temperature of the combustion products in the boiler and the overall heat-transfer coefficient-area products of the boiler and the condenser.

INPUTS

- T_{cond} - temperature of steam in condenser
- T_{be} - temperature of steam leaving boiler
- P_b - pressure of steam in boiler
- η_t - isentropic efficiency of turbine
- H_{fg} - heat capacity rate of flue gas stream
- T_{fb} - temperature of flue gas leaving boiler

- T_{ab} - temperature of combustion air entering boiler
(leaving air preheater)
- T_{amb} - temperature of ambient air
- E_b - rate at which energy is released by combustion
in boiler
- L_{H_2} - energy loss rate due to evaporation of H_2O formed
by combustion of hydrogen in fuel (latent heat loss
due to hydrogen in fuel)
- L_w - energy loss rate due to evaporation of water in fuel
(latent loss due to water in fuel)
- L_{cu} - energy loss rate due to carbon that does not burn
(unburned carbon loss)
- L_{rad} - energy loss rate due to radiation and unaccounted
for losses
- A_p - the value of the coefficient used in the equation
for parasitic power
- R_{eff} - ratio of Rankine cycle efficiency of simulated
cycle to Rankine cycle efficiency of simple cycle
- R_f - ratio of steam rate through boiler to steam rate
through condenser for simulated cycle
- C_{pw} - specific heat of (liquid) water
- T_{wi} - temperature of cooling water entering condenser
- T_{we} - temperature of cooling water leaving condenser
- η_g - efficiency of generator

OUTPUTS

- p_{cond} - pressure of steam in condenser
- h_{ce} - specific enthalpy of condensate leaving condenser
(entering boiler)
- T_{bs} - saturation temperature of steam at boiler pressure
- h_{gs} - specific enthalpy of saturated steam at boiler pressure

- h_{be} - specific enthalpy of steam leaving boiler (entering turbine)
- s_{ce} - specific entropy of condensate leaving condenser
- s_{be} - specific entropy of steam leaving boiler
- h_{ci} - specific enthalpy of steam entering condenser (leaving turbine)
- L_{sen} - energy loss rate due to the higher-than-ambient temperature of the flue gases leaving the air preheater (sensible heat loss)
- Q_b - rate of heat transfer from combustion products to steam in boiler
- T_f - flame temperature of combustion products
- P_t - power output of turbine
- Q_c - rate of heat transfer from condensing steam to cooling water in condenser
- F_c - flow rate of steam through condenser
- F_w - flow rate of cooling water through condenser
- F_b - flow rate of steam through boiler
- P_g - power output of generator
- R_p - fraction of generated electrical power needed to operate power plant (parasitic power ratio)
- η_{rc} - efficiency of Rankine cycle
- UA_b - overall heat-transfer coefficient-area product of boiler
- UA_c - overall heat-transfer coefficient-area product of condenser

EQUATIONS

$$\begin{aligned}
 P_{cond} &= (18168500 \text{ psia}) \exp(-9394.238^\circ\text{R}/T_{cond}) \\
 h_{ce} &= (-31.92724 \text{ Btu/lbm}) + (0.9990623 \text{ Btu/lbm}^\circ\text{F}) T_{cond} \\
 T_{bs} &= -8350.663^\circ\text{R} / [\ln(P_b/4101897 \text{ psia})] \\
 h_{gs} &= [1067.544 \text{ Btu/lbm}] / [1 - 0.812079 / \ln(P_b/0.443934 \text{ psia})]
 \end{aligned}$$

$$\begin{aligned}
h_{be} &= h_{gs} - (20.63059 \text{ Btu/lbm}) + (0.04879296 \text{ Btu/lbm psia}) P_b \\
&\quad + (0.6294891 \text{ Btu/lbm } ^\circ\text{F}) (T_{be} - T_{bs}) \\
s_{ce} &= (0.9988549 \text{ Btu/lbm } ^\circ\text{R}) \ln(T_{cond}/491.621 ^\circ\text{R}) \\
s_{be} &= (0.0008620966 ^\circ\text{R}^{-1}) h_{be} - (0.09885418 \text{ Btu/lbm } ^\circ\text{R}) \ln(p_b/40984.82 \text{ psia}) \\
h_{ci} &= h_{be} - \eta_t [h_{be} - h_{ce} - T_{cond}(s_{be} - s_{ce})] \\
L_{sen} &= H_{fg}(T_{fg} - T_{amb}) \\
Q_b &= E_b - L_{sen} - L_{H2} - L_w - L_{cu} - L_{rad} \\
T_f &= T_{fg} + Q_b/H_{fg} \\
P_t &= Q_b R_{eff} (h_{be} - h_{ci}) / (h_{be} - h_{ce}) \\
Q_c &= Q_b - P_t \\
F_c &= Q_c / (h_{ci} - h_{ce}) \\
F_w &= Q_c / [C_{pw}(T_{we} - T_{wi})] \\
F_b &= F_c R_f \\
P_g &= \eta_g P_t \\
R_p &= (A_p/100\text{MW})(P_g/100\text{MW})^{-0.14} \\
\eta_{rc} &= P_t/Q_b \\
UA_b &= Q_b \ln([T_f - T_{be}]/[T_{fb} - T_{cond}]) / [T_f - T_{be} - (T_{fb} - T_{cond})] \\
UA_c &= Q_c \ln([T_{cond} - T_{wi}]/[T_{cond} - T_{we}]) / (T_{we} - T_{wi})
\end{aligned}$$

ENERGY PLANTATIONTM CALCULATIONS (SUBROUTINE ENPLANT).

These calculations determine the Energy PlantationTM size, average cutting rate, and chip storage volume needed for the power plant to operate at the specified conditions.

INPUTS

- F_f - rate at which fuel is delivered to power plant
- F_{odfb} rate at which oven-dry fuel is supplied to the boiler
- L_f - ratio of annual average generated electrical power to full load capacity of generator (power plant load factor)

- τ_d - average harvesting time per day of harvesting operation
 D_y - average number of harvesting days per year
 ρ_{odf} density of oven-dry fuel
 Y_a - average yield density of oven-dry fuel from Energy PlantationTM
 τ_{sto} length of time for which power plant must be capable of operating on stored fuel
 ω_{odf} mass fraction of oven-dry fuel in as-delivered fuel

OUTPUTS

- R_{cut} - average cutting rate needed to supply fuel to the power plant at the specified rate
 V_{sto} - storage size needed to store enough fuel to provide power plant operation for the specified time interval
 F_{odfp} average rate at which oven-dry fuel is supplied to the power plant
 A_w - plantation area needed to provide fuel to the power plant at the specified rate on a sustained basis

EQUATIONS

$$\begin{aligned}
 R_{cut} &= F_f L_f / \tau_d \\
 V_{sto} &= F_{odfb} D_y / \rho_{odf} \\
 F_{odfp} &= F_f L_f \omega_{odf} \\
 A_w &= F_{odfp} / Y_a
 \end{aligned}$$

COST CALCULATIONS (SUBROUTINE PPCOST)

These calculations determine the cost per unit of electrical energy generated, by both the utility method and the municipal method of financing. An explanation of these financing methods and the associated calculations is shown in Appendix A.

INPUTS

- C_{fa} - unit cost of oven-dry fuel by utility method of financing
- C_{fm} - Unit cost of oven-dry fuel by municipal method of financing
- D_f - fraction of costs to be financed by borrowed capital
(for utility method)
- i_d - annual interest rate on borrowed capital (for utility method)
- i_e - desired after-tax rate of return on equity (for utility method)
- i_m - rate of return (for municipal method)
- N - total period of investment for power plant
- L_f - ratio of annual average generated electrical power to full load capacity of generator (power plant load factor)
- P_g - full load power output of generator
- F_{odfp} - rate at which oven-dry fuel is supplied to power plant

OUTPUTS

- i_u - composite discounting rate (utility method)
- C_{cap} - capital cost of power plant
- T_{const} - time required for power plant construction
- C_{dcu} - interest paid during construction (utility method)
- C_{dcm} - interest paid during construction (municipal method)
- C_{aom} - annual operation and maintenance cost
- C_{afu} - annual fuel cost by utility method of financing
- C_{afm} - annual fuel cost by municipal method of financing
- C_{lwcu} - working capital and land cost by utility method of financing
- C_{lwcm} - working capital and land cost by municipal method of financing
- C_{adiu} - annual depreciable investment cost (utility method)
- C_{adim} - annual depreciable investment cost (municipal method)
- C_{andiu} - annual nondepreciable investment cost (utility method)
- C_{andim} - annual nondepreciable investment cost (municipal method)
- C_{it} - annual federal income tax cost (utility method only)

- C_{atru} - annual total revenue required (utility method)
 C_{atrm} - annual total revenue required (municipal method)
 E_s - average amount of generated electrical energy sold
per year
 C_{pu} - unit electricity cost (utility method)
 C_{pm} - unit electricity cost (municipal method)

EQUATIONS

$$i_u = i_d D_f + i_e (1 - D_f)$$

$$C_{cap} = \begin{cases} (47.9 \times 10^6 \text{ 1976 dollars}) + (468 \text{ 1976 dollars/kw})P_g & P_g \geq 86400 \text{ kW} \\ (18.7 \times 10^6 \text{ 1976 dollars}) + (806 \text{ 1976 dollars/kw})P_g & P_g < 86400 \text{ kW} \end{cases}$$

$$T_{const} = (1.74 \text{ years}) + (4.26 \times 10^6 \text{ years/Kw})P_g$$

$$C_{dcu} = T_{const} C_{cap} i_u / 2$$

$$C_{dcm} = T_{const} C_{cap} i_m / 2$$

$$C_{aom} = (1.96 \times 10^6 \text{ 1976 dollars}) + (2.66 \text{ 1976 dollars/kw})P_g$$

$$C_{afu} = C_{fu} F_{odfp}$$

$$C_{afm} = C_{fm} F_{odfp}$$

$$C_{lwc u} = (C_{aom} + C_{afu}) / 6$$

$$C_{lwc m} = (C_{aom} + C_{afm}) / 6$$

$$C_{adiu} = i_u (1 + i_u)^N (C_{cap} + C_{dcu}) / [(1 + i_u)^N - 1]$$

$$C_{adim} = i_m (1 + i_m)^N (C_{cap} + C_{dcm}) / [(1 + i_u)^N - 1]$$

$$C_{andiu} = i_u C_{lwc}$$

$$C_{andim} = i_m C_{lwc}$$

$$S_d = [1/i_u] - N / [(1 + i_u)^N - 1]$$

$$C_{adu} = 2(C_{cap} + C_{dcu}) (N - S_d) / [N(N + 1)]$$

$$C_{it} = 48 (C_{adiu} - C_{adu} + C_{andiu}) (1 - D_f) i_e / 52 i_u$$

$$C_{atru} = C_{aom} + C_{af} + C_{adiu} + C_{andiu} + C_{it}$$

$$C_{atrm} = C_{aom} + C_{af} + C_{adim} + C_{andim}$$

$$E_s = P_g L_f$$

$$C_{pu} = C_{atru}/E_s$$

$$C_{pm} = C_{atrm}/E_s$$

APPENDIX E
REQUESTS FOR INFORMATION FROM STATE ENERGY OFFICES

Inquiries were sent to the 48 conterminous states to gather information concerning potential sites for a demonstration PEF. In this appendix are listed the names and addresses of those state agencies queried and a sample of the letter sent. Several letters were sent to each state to various agencies because it was not known beforehand which state office would have the desired information.

INTERTECHNOLOGY CORPORATION

100 MAIN STREET, WARRENTON, VIRGINIA 22186, U.S.A., TELEPHONE 703-347-7900

20 January 1977

Mr. R. C. Bamberg, Chairman
Director, Alabama Development Office
Energy Management Board
Executive Building, Suite 203
312 Montgomery Street
Montgomery, Alabama 36104

Dear Mr. Bamberg:

Our firm, InterTechnology Corporation, has been contracted by the U.S. Energy Research and Development Administration to develop an alternate energy concept we have named the Photosynthesis Energy Factory. In this concept, electricity is generated from plants specifically grown for their fuel value, and synthetic natural gas is produced by anaerobic digestion of algae grown in lagoons utilizing stack gases and other nutrient-containing effluents. The total process is essentially nonpolluting and continuously renewable.

Currently, we are in the process of evaluating specific locations for a working, full-scale demonstration of this concept. Based on the data we collect, we will recommend sites as candidates for federally-funded demonstration experiments. Your office can participate in this program by helping to provide the technical data we require to evaluate potential demonstration sites in your state.

We have included with this letter a brief list of eight points describing in general terms the information we need. Will you please identify counties in your state where any of the eight conditions exist? If you require further information concerning this project, please call me or Mr. Charles Vail at (703) 347-7900.

We invite you to contact ERDA to verify their interest and long-range plans for this project. The project is under the direct control of Dr. Roscoe Ward, Biomass Energy Program, U.S. ERDA, Washington, D. C. The specific title and contract number for this ITC project is "The Photosynthesis Energy Factory", ERDA Contract No. E(49-18)2548.

Very truly yours,

Norris L. Beard
Program Manager

NLB:jwg

Enclosure

SITE SURVEY INFORMATION SHEET
FOR THE
PHOTOSYNTHESIS ENERGY FACTORY

1. Land Resources - In which counties is land less suitable for the production of agricultural crops, or overall farm profit per acre are low?
2. Unusable Forest Resources - In which counties do, for example, forest areas contain a large fraction of hardwoods and nearby forest product industries use softwoods?
3. Cooling Water - Which flowing bodies of water will the current environmental quality standards permit use as a source of cooling water?
4. Nutrient-Rich Effluents - What are the locations of potential supplies of nontoxic, high BOD (biological oxygen demand) nutrient-rich effluents such as from dairy products processing or beef feedlots?
5. Dry Residues - What are the locations of potential supplies of dry cellulosic residues such as forest and farming crop residues, and the like?
6. Available Labor - In which counties is there high unemployment in the construction trade?
7. Market for Electricity - In which counties are there potential users of electric power, such as an electric cooperative which purchases part of the power it sells or an industry which generates some of the electricity it uses?
8. Market for Synthetic Natural Gas - In which counties are there potential industrial users of synthetic natural gas?

Mr. Nick C. Ruffin
Coordinator, Energy Policy and Planning
State Energy Office
325 National Old Line Building
Little Rock, Arkansas 72201

Mr. Richard M. Maullin
Chairman
Energy Resources Conservation and
Development Commission
455 Capitol Mall
Room 120
Sacramento, California 95814

Mr. Thomas J. Vogenthaler
Director
Colorado Energy Research Institute
P. O. Box 366
Golden, Colorado 80401

Mr. Damon W. Agee, Jr.
State Energy Director
State Energy Office
108 Collins Building
Tallahassee, Florida 32304

Mr. Lewis C. Spruill, Director
State Energy Office
7 Hunter Street
Room 145
Atlanta, Georgia 30334

Mr. Richard L. Brown, Director
State Office of Energy
300 North Sixth Street
Capitol Park Plaza Building
Boise, Idaho 83720

Mr. J. Ernest Dunwoody
Manager, Conservation and Alternate Energy
Division of Energy
Dept. of Business & Economic Development
222 South College Avenue
Springfield, Illinois 62706

Mr. Robert Berlin
Research and Development Specialist
Indiana Energy Office
803 State Office Building
Indianapolis, Indiana 46204

Dr. Laurent Hodges
Research Director
Energy Policy Council
Valley Bank Building
300 Fourth Street
Des Moines, Iowa 50319

Mr. Lamar Weaver, Director
Kansas Energy Office
503 Kansas Avenue
Room 241
Topeka, Kansas 66603

Mr. John M. Stapleton, Director
Kentucky Energy Office
Capital Plaza Tower
Frankfort, Kentucky 40601

Mr. Thomas C. Landrum
Chief, Natural Resources and Energy
Division of Natural Resources & Energy
Department of Conservation
State Land & Natural Resources Building
P. O. Box 44275
Baton Rouge, Louisiana 70804

Mr. Gary Linton
Acting Manager
State Fuel Allocation and
Conservation Office
State House
Augusta, Maine 04330

Mr. John P. Hewitt, Director
Energy Policy Office
219 West Hoffman Street
Baltimore, Maryland 21201

Mr. Henry Lee, Director
Energy Policy Office
One Ashburton Place
Room 1413
Boston, Massachusetts 02108

Mr. Richard Helmbrecht, Director
Department of Commerce
4th Floor Law Building
Lansing, Michigan 48913

Dr. James Carter
Director of Research
Minnesota Energy Agency
740 American Center Building
160 East Kellogg Boulevard
St. Paul, Minnesota 55101

Mr. George A. Cochran
State Fuel Coordinator
Fuel and Energy Management Commission
1307 Woolfolk State Office Building
Jackson, Mississippi 39205

Mr. Weston Fisher
Program Director
Missouri Energy Agency
P. O. Box 1309
Jefferson City, Missouri 65101

Mr. Jim Nybo
Energy Research Coordinator
Energy Advisory Council
c/o Lt. Governor's Office
Capitol Building
Helena, Montana 59601

Mr. William E. Peters
State Energy Coordinator and
State Tax Commissioner
State Office of Petroleum Allocation
P. O. Box 94841
Lincoln, Nebraska 68509

Mr. Phil Weymouth
Director, Resources Development
Governor's Council on Energy
3 Capitol Street
Concord, New Hampshire 03301

Mr. Charles Richman
Administrator
State Energy Office
101 Commerce Street
Newark, New Jersey 07102

Mr. Darren Luche
Deputy Administrator
Energy Resources Board
P. O. Box 2770
Santa Fe, New Mexico 87501

Mr. Pat Williams
Senior Fuel and Energy Researcher
Energy Division
Department of Military and
Veterans Affairs
215 East Lane Street
Raleigh, North Carolina 27611

Mr. Peter Susey
Chief of Policy Development
Energy Emergency Commission
30 East Broad Street
25th Floor
Columbus, Ohio 43215

Mr. Richard G. Hill, Director
Department of Energy
440 North Lincoln Boulevard
Suite 251
Oklahoma City, Oklahoma 73105

Mr. Lon Topaz, Director
Department of Energy
528 Cottage, N.E.
Salem, Oregon 97310

Mr. William B. Harral
Executive Director
Governor's Energy Council
Room 905
Payne-Shoemaker Building
Harrisburg, Pennsylvania 17101

Mr. David S. Harter
Director
Energy Management Office
1429 Senate Street
Columbia, South Carolina 29201

Mr. Max Gors, Director
Office of Energy Policy
State Capitol
Pierre, South Dakota 57501

Mr. Michael Huggins
Research and Development
Tennessee Energy Office
250 Capitol Hill Building
Nashville, Tennessee 37219

Mr. Alvin C. Askew
Executive Director
Governor's Energy Advisory Council
411 West 13th Street
Austin, Texas 78701

Mr. Clifford R. Collings
State Energy Coordinator
Interdepartmental Coordinating Council
for Energy Affairs
438 State Capitol
Salt Lake City, Utah 84114

Mr. Forrest E. Orr, Director
State Energy Office
State Office Building
110 State Street
Montpelier, Vermont 05602

Mr. Louis R. Lawson, Jr.
Director
Virginia Energy Office
823 East Main Street, Room 300
Richmond, Virginia 23219

Mr. Keith Sherman
Energy Management Coordinator
Office of Energy Management and
Administration
Dept. of General Administration
219 General Administration Building
Olympia, Washington 98504

Mr. W. Keith Zillifro, Director
Fuel and Energy Office
1262 1/2 Greenbrier Street
Charleston, West Virginia 25311

Mr. Stephen Born, Director
State Planning Office
One West William Street
Room B-158
Madison, Wisconsin 53702

Mr. Robert Gall
Operations Coordinator
Department of Planning and Development
Capitol Building
Charleston, West Virginia 25305

Mr. Nicolas Lewis
Assistant Director
Office of Program Planning and Fiscal Management
State Planning Division
House Office Building
Olympia, Washington 98504

Mr. Stanley Kidwell
Associate Director for Local and Regional Planning
Division of State Planning and Community Affairs
1010 James Madison Building
109 Governor Street
Richmond, Virginia 23219

Mr. Bernard D. Johnson
Assistant Director
State Planning Office
Pavilion Office Building
Montpelier, Vermont 05602

Mr. Burton Carlson
State Planning Coordinator
State Planning Agency
118 State Capitol
Salt Lake City, Utah 84114

Mrs. Jean O. Williams
Chief of Natural Resources Section
Division of Planning Coordination
Office of the Governor
411 W. 13th Street
Austin, Texas 78711

Mr. Niles C. Schoening, Director
State Planning Office
660 Capitol Hill Building
Nashville, Tennessee 37219

Mr. Arthur Wilner
Policy Analyst
State Planning Bureau
State Capitol
Pierre, South Dakota 57501

Dr. H. Wayne Beam
Deputy Executive Director
Land Resources Conservation
Commission
P. O. Box 11708
Columbia, South Carolina 29211

Mr. Daniel Varin, Chief
Statewide Planning Program
Department of Administration
265 Melrose Street
Providence, Rhode Island 02907

Mr. Robert Benko
Chief of Long Range Planning
Office of State Planning and
Development
510 Finance Building
Harrisburg, Pennsylvania 17127

Mr. Harold Brauner, Director
Conservation and Development
Commission
1175 Cort Street, N.E.
Salem, Oregon 97310

Mr. Gary Witt
Director State Planning and
Management
Department of Economic and
Community Affairs
4901 North Lincoln
Oklahoma City, Oklahoma 73105

Mr. Dave LaValle
Acting Administrator
Planning Services
Department of Natural Resources
Fountain Square
Building E-Floor 5
Columbus, Ohio 43224

Mr. Russell Staiger
Planning Administrator
State Planning Division
State Capitol
Bismarck, North Dakota 58501

Mr. Steve Thompson
Assistant State Officer for
Land Use Policy
Office of State Planning
Department of Administration
Administration Building
West Jones Street
Raleigh, North Carolina 27603

Mr. Hugh O'Neill
Assistant Director
Division of State Planning
Alfred E. Smith Office Building
Albany, New York 12225

Ms. Grace Olivares, Director
State Planning Office
State Capitol
Santa Fe, New Mexico 87503

Mr. Richard Binetsky, Chief
Bureau of Regional Planning
Division of State and Regional Planning
329 West State Street
Trenton, New Jersey 08625

Mr. George McAvoy, Director
Office of Comprehensive Planning
Division of State Planning
122 State House
Concord, New Hampshire

Mr. John Meder, Director
Land Use Planning Agency
201 South Fall Street
Carson City, Nevada 89701

Mr. Don Nelson, Director
State Office of Planning and Programming
P. O. Box 94601
Lincoln, Nebraska 68509

Mr. Byron Roberts
Bureau Chief
State Land Use Planning Bureau
Department of Community Affairs
Capitol Post Office
Helena, Montana 59601

Mr. Bill Cramer, Director
Division of State Planning and Analysis
Capitol Building
Jefferson City, Missouri 65101

Dr. Kenneth Wagner, Director
Research and Development Center
P. O. Drawer 2470
Jackson, Mississippi 39205

Mr. Roger Williams
Manager, Land Use Planning
State Planning Agency
100 Capitol Square Building
St. Paul, Minnesota 55101

Mr. Paul Wileden, Director
Office of Intergovernmental Relations
Department of Management and Budget
Lewis Cass Building
Lansing, Michigan 48913

Mr. Frank Keefe, Director
Office of State Planning
100 Cambridge Street
Room 909
Boston, Massachusetts 02202

. Edwin Thomas
Director, Comprehensive State Planning
Department of State Planning
301 West Hoffman Street
Baltimore, Maryland 21201

Mr. Allen Pease, Director
State Planning Office
State House
Augusta, Maine 04330

Mr. Eddie L. Schwertz, Jr.
Land Use Planning Coordinator
State Planning Office
P. O. Box 44425
Baton Rouge, Louisiana 70804

Mr. Billy S. Lewis
Commissioner, Bureau of Land Resources
Department for Natural Resources and
Environmental Protection
Capital Plaza Tower
Frankfort, Kentucky 40601

Mr. Dale Peterson, Local Planner
Planning Division
Department of Economic Development
State Office Building
Topeka, Kansas 66612

Mr. Robert F. Tyson, Director
Office of Planning and Programming
523 East 12th Street
Des Moines, Iowa 50319

Mr. Eugene Waterstraat
Assistant Director State Planning
State Planning Services
143 West Market Street
Indianapolis, Indiana 46204

Mr. Thomas Langford
Assistant Bureau Director
Growth and Development Planning
Bureau of the Budget
216 East Monroe Street
Springfield, Illinois 62706

Mr. Robert N. Wise, Chief
Bureau of State Planning and
Community Affairs
State House
Boise, Idaho 83720

Mr. Larry Gess
Coordinator of Divisional Planning
Office of Planning and Budget
270 Washington Street, S.W.
Atlanta, Georgia 30334

Mr. Helge Swanson, Bureau Chief
Bureau of Comprehensive Planning
Division of State Planning
660 Apalachee Parkway
Tallahassee, Florida 32301

Mr. David S. Hugg III
Principal Planner
Environmental Policy and Community
Development Services
State Planning Office
Thomas Collins Building
Dover, Delaware 19901

Mr. Horace Brown
Director of Interagency Coordination
Department of Planning and Energy Policy
480 Capitol Avenue
Hartford, Connecticut 06115

Mr. Phillip Savage
Staff Director
Land Use Commission
1550 Lincoln, Room 103
Denver, Colorado 80203

Mr. Preble Stolz, Director
Office of Planning and Research
1400 Tenth Street
Suite 256
Sacramento, California 95814

Mr. Ron Copland, Director
Department of Local Services
400 Train Station
Little Rock, Arkansas 72201

Mr. Harry F. Higgins
State Planning Director
Office of Economic Planning and Development
1645 Jefferson Street
Phoenix, Arizona 85007

Mr. Bill J. Starnes
Director, State Planning
Alabama Development Office
State Office Building
Montgomery, Alabama 36104

Mr. David B. Freudenthal
State Planning Coordinator
State Planning Coordinator's Office
Office of the Governor
State Capitol
Cheyenne, Wyoming 82002

Mr. John Armstrong
Energy Planner
State Planning Office
One West William Street
Room B-158
Madison, Wisconsin 53702

Mr. Jeff Herholdt
Office of Federal-State Relations
Department of Planning and Development
Capitol Building
Charleston, West Virginia 25305

Mr. Joseph Lightfoot
Executive Secretary
Thermal Power Plant Site Evaluation
Council
820 East Fifth Avenue
Olympia, Washington 98504

✓ Mr. Ernest Jordan
Division Director
Division of Public Utilities
State Corporation Commission
P. O. Box 1197
Richmond, Virginia 23209

Mr. Martin Miller, Chairman
Public Service Board
State Office Building
Montpelier, Vermont 05602

Mr. N. B. Hughes
Director of Power Resource Planning
Tennessee Valley Authority
403 Power Building
Chattanooga, Tennessee 37402

Mr. Dan Bucks, Commissioner
State Planning Bureau
State Capitol
Pierre, South Dakota 57501

Mr. R. Franklin Barrett
Conservation Engineer
Energy Management Office
1429 Senate Street
Columbia, South Carolina 29201

Mr. Glenn KumeKawa
Policy and Planning Assistant
Governor's Office
State House
Providence, Rhode Island 02903

Mr. Herbert Jacobs
Energy Park Coordinator
Governor's Energy Council
Capitol Building
Harrisburg, Pennsylvania 17120

Dr. Kelly Woods, Administrator
Energy Facility Siting Division
Department of Energy
528 Cottage, N.E.
Salem, Oregon 97310

Mr. Rex Privett, Chairman
Corporation Commission
Jim Thorpe Office Building
Oklahoma City, Oklahoma 73105

Mrs. Lola Dickerman, Chairman
Energy Facilities Siting Council
Executive Office of Consumer Affairs
McCormack Office Building
Boston, Massachusetts 02108

Mr. Lee E. Zeni, Administrator
Energy, Mining and Coastal Zinc Management
Administration
Department of Natural Resources
Tawes State Office Building
Annapolis, Maryland 21401

Mr. William Adams, Commissioner
Department of Environmental Protection
State House
Augusta, Maine 04330

Mr. William A. Logan, Chairman
Public Service Commission
Capital Plaza Tower
Frankfort, Kentucky 40601

Mr. Maurice Van Nostrand, Chairman
State Commerce Commission
Walnut and Fourth Streets
Des Moines, Iowa 50319

Mr. Thomas Kibler, Director
Indiana Energy Office
803 State Office Building
Indianapolis, Indiana 46204

Mr. Marvin Lieberman, Chairman
Illinois Commerce Commission
527 East Capitol Avenue
Springfield, Illinois 62706

Mr. Robert Lenaghan, President
Public Utilities Commission
472 W. Washington Street
Boise, Idaho 83720

Mr. Chart Bonham
Deputy Director
State Energy Office
7 Hunter Street
Room 145
Atlanta, Georgia 30334

Mr. Hamilton S. Oven, Jr.
Administrator Power Plant Siting Program
Department of Environmental Regulation
2562 Executive Center Circle East
Tallahassee, Florida 32301

Mr. N. C. Vasuki, Director
Division of Environmental Control
Department of Natural Resources
Tatnall Building
Dover, Delaware 19901

Mr. L. K. Christolear
Supervising Engineering Analyst
Public Utilities Commission
1845 Sherman Street
Denver, Colorado 80203

Mr. Robert C. Downie, Chairman
Public Service Commission
Justice Building
Little Rock, Arkansas 72201

Dr. Brent Brown
Executive Director
Power Plant Siting Commission
Office of Economic Planning and Development
1645 Jefferson Street
Phoenix, Arizona 85007

Mr. Edwin G. Hudspeth
Executive Director
Ameraport Offshore Harbor and Terminal
Commission
203 Executive Building
312 Montgomery Street
Montgomery, Alabama 36104

Mr. John T. Goodier
Chief of Mineral Development and
Fuel Allocation Officer
Mineral Development Division
Department of Economic Planning and
Development
720 West 18
Cheyenne, Wyoming 82002

Dr. Charles J. Cicchetti, Director
Office of Energy Emergency Assistance
P. O. Box 5368
Madison, Wisconsin 53705

Mr. Thomas Bantz
Power Siting Coordinator
Power Siting Commission
Seneca Towers
361 East Broad Street
Columbus, Ohio 43215

Mr. Al Bumann, Director
Energy Conversion and Transmission
Facility Siting Division
Public Service Commission
State Capitol
Bismarck, North Dakota 58501

Mr. Andrew W. Williams
Chief of Electric Division
Utilities Commission
Department of Commerce
Ruffin Building
1 West Morgan Street
Raleigh, North Carolina 26702

Dr. Alfred Kahn, Chairman
Board on Electric Generation,
Siting and Environment
Department of Public Service
44 Holland Avenue
Albany, New York 12208

Mr. Cloin Robertson
Siting Program Manager
Atomic and Space Development Authority
Saratoga Research and Development Center
Plains Road
Ballston Spa, New York 12020

Dr. Gilbert L. Canó
Governor's Science and Energy Advisor
Office of the Governor
State Capitol
Santa Fe, New Mexico 87503

Mr. Thomas Seesell
Deputy Commissioner
Department of Environmental Protection
P. O. Box 1390
Trenton, New Jersey 08625

Mr. William A. Healy, Chairman
Site Evaluation Committee
c/o Public Utilities Commission
26 Pleasant Street
Concord, New Hampshire 03301

Mr. Noel A. Clark, Chairman
Public Service Commission
202 South Carson
Carson City, Nevada 89701

Mr. Gary Gustafson
Executive Secretary
Power Review Board
1220 J Street
Farmers Mutual Building
Lincoln, Nebraska 68509

Mr. Albert C. Tsao, Administrator
Energy Planning Division
Department of Natural Resources and
Conservation
32 South Ewing
Helena, Montana 59601

Mr. A. Robert Pierce, Jr., Chairman
Public Service Commission
Jefferson Building
Jefferson City, Missouri 65101

Mr. Norman A. Johnson, Jr.
Chairman
Public Service Commission
P. O. Box 1174
Jackson, Mississippi 39205

Mr. Emmitt Moore
Manager, Power Site Planning
State Planning Agency
100 Capitol Square Building
St. Paul, Minnesota 55101

Mr. William G. Rosenberg, Chairman
Public Service Commission
525 West Ottawa Street
Lansing, Michigan 48913

Mr. David S. Harter, Director
Energy Management Office
1429 Senate Street
Columbia, South Carolina 29201

Mr. William D. Robinson
Petroleum Allocation Manager
Office of Energy Management
P. O. Box 1817
Bismarck, North Dakota 58501

Judge John Collins, Chairman
State Energy Resources Advisory Board
302 East Carson
Suite 800
Las Vegas, Nevada 89101

Mr. James W. McCloskey
Director
Division of Emergency Planning and
Operations
Department of Public Safety
P. O. Box C
Delaware City, Delaware 19706

Mr. Joseph A. Belanger
Director, Research and Policy Development
Department of Planning and Energy Policy
20 Grant Street
Hartford, Connecticut 06115

Mr. Robert Handy
Director, Solar Energy Commission
Fuel Allocations Section
Office of Economic Planning and Development
1645 West Jefferson
Room 428
Phoenix, Arizona 85007

Ms. Pan Schnook
New York Legislative Commission on
Energy Systems
828 Legislative Office Building
Albany, New York 12224

APPENDIX F

EXPERIMENTAL ANALYSIS OF JUVENILE WOODY BIOMASS

This appendix contains the results of experimental analysis performed on juvenile poplar wood. Seven hybrids of poplar were chosen as candidates:

- (1) to gain some idea of intragenus variation in the various values;
and
- (2) to measure the consistency of the data.

The objective of the analysis was to provide information on chemical and thermal properties of juvenile wood for designing the Energy PlantationTM, the power plant, and the algae ponds, i.e., the PEF. In addition, the analysis confirmed that earlier analyses in the literature of more mature wood commonly used as a forest industry raw material are not suitable for characterizing juvenile Energy PlantationTM biomass.

These analyses were performed by P. R. Blankenhorn, T. W. Bowersox, and W. K. Murphey, consultants, in their laboratories at University Park, PA. This appendix contains their complete final report.

HEAT OF COMBUSTION, ASH CONTENT, NUTRIENT ANALYSIS,
AND CHEMICAL CONTENT OF POPULUS HYBRIDS

P. R. BLANKENHORN, T. W. BOWERSOX, AND W. K. MURPHEY

FINAL REPORT

TO

InterTechnology/Solar Corporation
100 Main Street
Warrenton, VA 22186

August 1977

PROCEDURE

Composite wood and bark specimens were obtained from 4-year-old trees of Populus hybrids. Parentage of these hybrids is presented in Table 1. Segmental specimens were obtained from clone NE-388 and were divided into roots (no bark), wood and bark of 1, 2, 3, and 4 years of age, 1- to 4-year-old bark, and 4-year-old leaves. All specimens (composite and segmental) were analyzed for gross heat of combustion, ash content, selected nutrient content, and chemical content.

Foliar samples, petioles removed, were collected near the end of the fourth growing season but before leaf coloration, dried at 80°C for 24 hours, and ground in a Wiley mill to pass through a 40-mesh screen. Wood and bark samples were collected from dormant trees and stored at -10°C until analysis. Root and bark collections were made in the early part of the growing season. Fresh wood and bark, bark, and root samples were ground to pass through a 40-mesh screen and oven-dried at 105°C for 24 hours. Material used for the chemical analyses was restricted to that which would pass through a 40-mesh, but was retained on a 60-mesh screen.

The seven Populus hybrids were planted at 0.6 x 0.6 m in a Weikert shaly, silt loam soil located in central Pennsylvania. Soil from the Ap horizon was collected at the time the trees were planted and analyzed by the Soil Testing Laboratory of The Pennsylvania State University according to the procedures outlined by Hinrich and others (1967). Nutrient levels of the selected Populus tissues were analyzed

TABLE 1 . Parentage of the seven Populus hybrids.

Clone	PARENTAGE	
	Female	Male
NE-49	<u>maximowiczii</u>	'Berolinensis'
NE-245	'Angulata'	<u>deltoides</u>
NE-252	'Angulata'	<u>trichocarpa</u>
NE-279	<u>nigra</u>	<u>laurifolia</u>
NE-302	'Betulifolia'	<u>trichocarpa</u>
NE-350	<u>deltoides</u>	<u>trichocarpa</u>
NE-388	<u>maximowiczii</u>	<u>trichocarpa</u>

spectrometrically for elemental P, K, Ca, and Mg and expressed in percentage of oven-dry weight (Baker and others 1964).

Gross heat of combustion tests were conducted in accordance with ASTM Standard D 2015-66 and the values are expressed in cal/g. Ash contents were determined on the ash that remained after the gross heat of combustion tests were completed and are expressed as percentage of oven-dry weight.

Chemical analysis of the specimens consisted of obtaining the percent total extractive in accordance with Tappi Standard T-19 m-50, percent holocellulose (acid chlorite method, Browning 1967), and percent pentosan in accordance with ASTM Standard D 1105-72. The percent total extractive values are expressed on an oven-dry weight basis, and both the percent holocellulose and percent pentosan are expressed on percent of extractive free oven-dry weight basis.

Analysis of variance was used to determine if significant clonal differences existed among the seven variables and if there were significant differences in the selected segments of clone NE-388 with regard to the seven variables. The Scheffé method for mean separation was used to test for significant differences among means within a treatment. All significant differences are indicated at the .05 level.

RESULTS AND DISCUSSION

SOIL ANALYSIS

Nutrients. The Weikert soil series consists of material weathered from noncalcareous shale. This type of soil generally has a shallow depth to bedrock. Depth to bedrock, for the plantation where these

specimens were obtained, ranged from 0.5 to 0.7 m. Weikert soils are used mostly for cultivated crops and are generally rated as fair in inherent fertility and low to very low in available moisture capacity. Gently sloping sites would usually be Soil Capability Class II or III. Specific nutrient levels for the central Pennsylvania site at which the specimen trees were growing are presented in Table 2.

COMPOSITE SPECIMENS

Tables 3-6 list the oven-dry gross heat of combustion, ash content, selected nutrient values and chemical analysis of combined wood and bark specimens from seven Populus hybrids (up to 4 years of age), respectively. A summary analysis of this data is given in Table 7.

Gross Heat of Combustion. Average gross heat of combustion for the composite specimens of seven Populus hybrids ranged from 4,606 to 4,705 cal/g. Statistical analysis of the data (Table 7) indicated that there was no significant difference among these seven clones. The pooled average for all clones is 4,659 cal/g (8,386 BTU/lb). The values obtained for the gross heat of combustion are within the range of values reported for both softwoods and hardwoods (Howard 1973, Lenk 1970, Murphey and Cutter 1974).

Ash Content. Average ash content for these composite specimens were all less than 1.2 percent of oven-dry mass, and statistical analysis indicated no significant difference among the seven clones. Overall average of all specimens is .80 percent of oven-dry weight, and any clone can be used to estimate the average ash content of all clones.

TABLE 2. Average¹ analysis of the Ap horizon for a Wiekert shaly, silt loam soil. Samples were collected at the time the trees were planted.

pH	6.0
Total nitrogen (% by wt)	0.17
Extractable phosphorus (ppm)	7.1
Exchangeable potassium (meq/100g)	0.27
Exchangeable calcium (meq/100g)	9.3
Exchangeable magnesium (meq/100g)	0.6
Cation exchange capacity (meg/100g)	14.1

¹Average of 10 samples.

TABLE 3. Owendry gross heat of combustion¹ for composite (1- through 4-year-old wood and bark) specimens from seven Populus hybrids.

GROSS HEAT OF COMBUSTION - OVENDRY							
Specimen	<u>Populus</u> Hybrid						
	NE-49	NE-245	NE-252	NE-279	NE-302	NE-350	NE-388
	----- (cal/g) -----						
1	4,693	4,583	4,661	4,754	4,700	4,857	4,827
2	4,665	4,551	4,690	4,735	4,649	4,642	4,657
3	4,714	4,578	4,589	4,624	4,662	4,592	4,584
4	4,907	4,690	4,680	4,716	4,682	4,622	4,807
5	4,599	4,649	4,646	4,603	4,659	4,415	4,582
6	4,288	4,674	4,667	4,674	4,877	4,508	4,739
AVERAGE	4,644	4,621	4,655	4,684	4,705	4,606	4,699

¹According to ASTM Standard D2015-66.

TABLE 4. Amount of ash¹ in composite (1- through 4-year-old wood and bark) specimens from seven Populus hybrids.

ASH CONTENT							
Specimen	<u>Populus</u> Hybrid						
	NE-49	NE-245	NE-252	NE-279	NE-302	NE-350	NE-388
	----- (% OD wt) -----						
1	.52	1.31	.79	.52	.73	2.00	.77
2	.51	1.53	.50	.37	.56	1.25	.67
3	.34	.54	.60	.54	.48	1.80	.60
4	1.40	.42	.58	.87	1.01	1.58	.97
5	.78	.28	1.09	.81	.90	.39	1.23
6	.27	.73	1.03	.48	1.16	.20	.68
AVERAGE	0.64	0.80	0.77	0.60	0.81	1.20	0.82

¹Ash that remained after complete combustion.

TABLE 5. Amount of P, K, Ca, and Mg for composite (1- through 4-year-old wood and bark)specimens from seven Populus hybrids.

PHOSPHORUS							
Specimen	<u>Populus</u> Hybrid						
	NE-49	NE-245	NE-252	NE-279	NE-302	NE-350	NE-388
----- (% OD wt) -----							
1	.07	.09	.06	.09	.08	.07	.09
2	.08	.08	.07	.09	.08	.08	.09
3	.09	.08	.07	.07	.08	.07	.08
4	.07	.07	.07	.09	.09	.08	.08
5	.06	.07	.07	.09	.10	.09	.09
6	.07	.07	.07	.09	.08	.08	.09
AVERAGE	.07	.08	.07	.09	.09	.08	.09
POTASSIUM							
Specimen	<u>Populus</u> Hybrid						
	NE-49	NE-245	NE-252	NE-279	NE-302	NE-350	NE-388
----- (% OD wt) -----							
1	.38	.35	.21	.38	.30	.33	.32
2	.42	.33	.37	.38	.28	.33	.42
3	.37	.34	.32	.28	.30	.36	.36
4	.38	.27	.36	.38	.40	.44	.30
5	.33	.24	.21	.41	.47	.40	.34
6	.35	.32	.34	.37	.44	.34	.38
AVERAGE	.37	.31	.30	.37	.36	.37	.35
CALCIUM							
Specimen	<u>Populus</u> Hybrid						
	NE-49	NE-245	NE-252	NE-279	NE-302	NE-350	NE-388
----- (% OD wt) -----							
1	.47	.55	.66	.69	.54	.57	.58
2	.48	.59	.65	.74	.56	.57	.64
3	.51	.58	.62	.74	.54	.53	.58
4	.44	.59	.64	.69	.55	.55	.63
5	.41	.55	.65	.69	.55	.59	.66
6	.43	.58	.63	.71	.54	.58	.66
AVERAGE	.46	.57	.64	.71	.55	.57	.63
MAGNESIUM							
Specimen	<u>Populus</u> Hybrid						
	NE-49	NE-245	NE-252	NE-279	NE-302	NE-350	NE-388
----- (% OD wt) -----							
1	.06	.06	.05	.05	.06	.07	.04
2	.06	.06	.05	.06	.06	.07	.05
3	.06	.06	.05	.05	.06	.06	.05
4	.06	.06	.06	.05	.06	.06	.05
5	.06	.06	.05	.05	.07	.06	.05
6	.06	.07	.05	.05	.06	.07	.05
AVERAGE	.06	.06	.05	.05	.06	.06	.05

TABLE 6. Amount of total extractive,¹ holocellulose,² and pentosan³ for composite (1- through 4-year-old wood and bark) specimens from seven Populus hybrids.

Specimen	EXTRACTIVE						
	<u>Populus</u> Hybrid						
	NE-49	NE-245	NE-252	NE-279	NE-302	NE-350	NE-388
	----- (% OD wt) -----						
1	4.6	3.8	15.8	11.0	10.5	10.7	21.2
2	22.5	4.0	21.2	10.3	10.9	10.0	17.9
3	10.0	7.0	14.1	10.6	10.8	10.2	16.7
4	8.4	8.4	13.4	11.1	11.2	10.3	17.7
5	9.0	13.1	13.1	13.1	11.7	11.5	17.7
6	14.3	8.4	16.4	12.1	11.5	11.4	15.6
AVERAGE	11.5	7.5	15.7	11.4	11.1	10.7	17.8
	HOLOCELLULOSE						
	----- (% extractive free -----						
	OD wt)						
1	76.6	70.2	62.1	68.5	58.6	60.9	72.1
2	74.9	72.4	59.2	69.5	60.5	60.0	67.9
3	72.7	71.6	53.8	67.3	59.4	80.8	69.5
4	--	--	--	--	--	--	--
5	--	--	--	--	--	--	--
6	--	--	--	--	--	--	--
AVERAGE	74.7	71.4	58.4	68.4	59.5	67.2	69.8
	PENTOSAN						
	----- (% extractive free -----						
	OD wt)						
1	--	--	--	--	--	--	--
2	--	--	--	--	--	--	--
3	--	--	--	--	--	--	--
4	17.2	18.2	15.1	19.0	14.0	16.4	20.0
5	16.3	16.4	12.5	16.9	11.9	15.4	17.7
6	17.3	18.4	15.9	20.2	11.7	15.5	14.6
AVERAGE	16.9	17.7	14.5	18.7	12.5	15.8	17.4

¹According to Tappi Standard T-19 m-50.

²By acid chlorite method (Browning, B. L. 1967. Methods of Wood Chemistry).

³According to ASTM Standard D1105-72.

TABLE 7. Average¹ gross heat of combustion, ash content, and selected nutrients and chemicals for seven Populus hybrids.

Clone	Gross Heat of Combustion	NUTRIENTS					CHEMICALS		
		Ash	Phosphorus	Potassium	Calcium	Magnesium	Total Extractives	Holo- cellulose	Pentosan
	(cal/g)	(% OD wt)						(% extractive free OD wt)	
NE-49	4,644a	0.64a	0.07a	0.37a	.46a	0.06a	11.5ab	74.7a	16.9ab
NE-245	4,620a	.80a	.08ab	.31a	.57b	.06a	7.4b	71.4a	17.7ab
NE-252	4,656a	.77a	.07a	.30a	.64c	.05b	15.7bc	58.4b	14.5ac
NE-279	4,684a	.60a	.09b	.37a	.71d	.05b	11.4ab	68.4abc	18.7b
NE-302	4,705a	.81a	.09b	.37a	.55b	.06a	11.1ab	59.5bc	12.5c
NE-350	4,606a	1.20a	.08ab	.37a	.57b	.06a	10.6ab	67.2abc	15.8abc
NE-388	4,699a	.82a	.09b	.35a	.63c	.05b	17.8c	69.8abc	17.4ab
AVERAGE	4,659	.80	.08	.35	.59	.06	12.2	67.1	16.2
Mean Square Error	12,968	.174	.00007	.0030	.0006	.00002	7.65	4.6	2.4

¹Clonal means are for N=6 except for holocellulose and pentosan values which are for N=3. Overall means are for N=42 except for holocellulose and pentosan values which are for N=21. Column means with the same letter are not significantly different at the .05 level.

Nutrient Analysis. Concentrations of P, K, Ca, and Mg measured in the composite specimens collected from the seven Populus hybrids are presented in Table 5. Statistical analysis indicated there were no significant differences in the accumulated amount of K among the seven clones, while there were two significantly different clonal groupings of accumulated P and Mg. Calcium was the most variable nutrient and showed four significantly different clonal groupings. Although there are significant differences among the clones for the four nutrients, there were no consistent parental trends. The ranges of average nutrient values on a percent of oven-dry weight was 0.07 to 0.09 for phosphorus, 0.30 to 0.37 for potassium, 0.46 to 0.71 for calcium, and 0.05 to 0.06 for magnesium. The range in the average levels of these nutrients is minor in terms of relative magnitude.

Based on overall average values, harvesting wood and bark from 4-year-old plantations would remove an estimated 0.8 kg of P, 3.5 kg of K, 5.9 kg of Ca, and 0.6 kg of Mg in every 1,000 kg of biomass. Assuming that a 4-year-old plantation would yield 30 t/ha, it can be expected that 24, 105, 177, and 18 kg/ha of P, K, Ca, and Mg, respectively, would be removed from biogeochemical cycle. Amounts of nutrients removed by harvesting selected clones would require a knowledge of accumulated biomass as well as nutrient concentrations for the particular clones. Harvest of other tissues would produce a different effect.

Chemical Analysis. Total extractives (percent of oven-dry weight) average values range from 7.4 to 17.8 percent. Previous work has shown the inclusion of greater percentages of rhytidome occurs in older trees, thus the composition of the bark changes with age and might account for

these differences (Binotto and Murphey 1975). Statistical analysis shows that the clones can be divided into three significantly different groups with an overall average of 12.2 percent of the oven-dry weight being extractive content.

Analysis of the holocellulose and pentosan fraction did show some significant difference among the clones, but the range in values is not large. Holocellulose values range from 58.4 to 74.7 percent of extractive free oven-dry weight, and pentosan values range from 14.5 to 17.7 percent of extractive free weight. The ranges in these values may be due to randomly differing amounts of bark mixed in with the various specimens.

SEGMENTAL ANALYSIS

Table 8 lists the individual specimen oven-dry gross heat of combustion, ash content, selected nutrient analysis and chemical analysis for the various segments of Populus hybrid NE-388. Table 9 is a summary of these analyses. In general, there appear to be four separate significantly different groupings: roots; 1- through 4-year-old wood and bark; 1- to 4-year-old bark; and 4-year-old leaves.

Gross Heat of Combustion. Analysis of the gross heat of combustion data shows no significant difference between any of the segments used in this study. The range in values is from 4,402 to 4,650 cal/g, and the overall mean is 4,568 cal/g (8,222 BTU/lb). Any of the segments tested can be used to estimate the overall average gross heat of combustion for the clone.

TABLE 8. Owendry gross heat of combustion, ash content, and selected nutrient and chemical values for segments of Populus hybrid NE-388.

Segment	Gross Heat of Combustion	Ash	NUTRIENTS				CHEMICALS		
			Phosphorus	Potassium	Calcium	Magnesium	Total Extractives	Holo- cellulose	Pentosan
	(cal/g)		----- (% OD wt) -----				(% extractive free OD wt)		
<u>Roots, 1- to 4-yr-old</u>									
<u>without bark</u>									
Specimen 1	4,162	.85	.05	.20	.11	.03	4.5	74.3	21.0
2	4,499	.92	.05	.10	.11	.03	4.7	72.1	17.7
3	4,546	.09	.05	.11	.12	.03	4.1	73.7	25.1
AVERAGE	4,402	.62	.05	.14	.11	.03	4.4	73.4	21.3
<u>1-yr-old wood</u>									
Specimen 1	4,704	1.00	.13	.44	.95	.08	23.5	72.4	20.8
2	4,722	.62	.12	.39	.97	.09	10.0	73.6	15.5
3	4,627	.90	.12	.39	1.11	.10	14.9	74.2	24.6
AVERAGE	4,684	.84	.12	.41	1.01	.09	16.1	73.4	20.3
<u>2-yr-old wood</u>									
Specimen 1	4,652	1.14	.09	.33	.77	.06	6.3	60.7	--
2	4,451	.79	.08	.25	.81	.06	6.0	60.2	15.9
3	4,484	.60	.09	.25	.79	.06	19.0	59.9	16.5
AVERAGE	4,529	.84	.09	.28	.79	.06	12.4	60.3	16.2
<u>3-yr-old wood</u>									
Specimen 1	4,503	.69	.06	.19	.55	.04	8.8	71.5	19.5
2	4,597	.44	.06	.18	.54	.04	9.4	72.1	17.9
3	4,630	.48	.07	.26	.52	.04	8.7	70.8	18.5
AVERAGE	4,577	.54	.06	.21	.59	.04	9.0	71.5	18.6

TABLE 8.--continued.

Segment	Gross Heat of Combustion	Ash	NUTRIENTS				CHEMICALS		
			Phosphorus	Potassium	Calcium	Magnesium	Total Extractives	Holo- cellulose	Pentosan
	(cal/g)		-----(% OD wt) -----				(% extractive free OD wt)		
<u>4-yr-old wood</u>									
Specimen 1	4,836	.92	.07	.31	.62	.05	11.2	68.5	17.1
2	4,505	.95	.07	.26	.68	.05	10.0	70.1	16.9
3	4,411	.34	.07	.28	.76	.05	11.1	72.3	15.2
AVERAGE	4,584	.74	.07	.28	.69	.05	10.8	70.3	16.4
<u>1- to 4-yr-old bark</u>									
Specimen 1	4,701	1.98	.10	.43	2.27	.08	35.9	40.5	15.7
2	4,650	.82	.10	.40	2.11	.07	37.1	42.3	16.1
3	4,599	1.58	.12	.49	2.41	.08	37.4	45.6	15.3
AVERAGE	4,649	1.46	.11	.44	2.26	.08	36.8	42.8	15.7
<u>4-yr-old leaves</u>									
Specimen 1	4,585	1.94	.287	2.12	1.44	.262	40.6	57.6	10.7
2	4,554	1.55	.294	2.12	1.40	.283	39.8	--	13.8
3	4,518	1.51	.312	2.28	1.32	.247	39.6	44.8	10.8
AVERAGE	4,552	1.67	.298	2.17	1.39	.264	40.0	51.2	11.8

TABLE 9. Average¹ gross heat of combustion, ash content, and selected nutrients and chemicals for segments of Populus hybrid NE-388.

Segment	Gross Heat of Combustion	NUTRIENTS					CHEMICALS		
		Ash	Phosphorus	Potassium	Calcium	Magnesium	Total Extractives	Holo-cellulose	Pentosan
	(cal/g)	(% OD wt)						(% extractive free OD wt)	
Roots, up to 4 yr old (without bark)	4,402a	0.62a	0.05a	0.14a	0.11a	0.03a	4.4a	73.4a	21.3a
1 yr old wood and bark	4,684a	0.84a	.12b	.41b	1.01b	.09b	16.1b	73.4a	20.3a
2 yr old wood and bark	4,529a	0.84a	.09c	.28c	.79c	.06cd	10.4b	60.3b	16.2ab
3 yr old wood and bark	4,577a	.54a	.06d	.21c	.54d	.04c	9.0b	71.5a	18.6a
4 yr old wood and bark	4,584a	.74a	.07d	.28c	.69cd	.05c	10.8b	70.3a	16.4ab
1 to 4 yr old bark	4,650a	1.46b	.11e	.44b	2.26e	.07bcd	36.8c	42.8c	15.7ab
4 yr old leaves	4,552a	1.67b	.30f	2.17d	1.39f	.26e	40.0c	51.2d	11.8b
AVERAGE	4,568	0.96	.11	.56	.96	.09	18.2	63.3	17.2
Mean Square Error	16,563	.124	.00005	.0027	.0056	.00005	14.79	7.71	5.68

¹Segment means are for N=3. Overall means are for N=21. Column means with the same letter are not significantly different at the .05 level.

Ash Content. Statistical analysis indicated that the average ash content of 1- to 4-year-old bark (1.46 percent) and the 4-year-old leaves (1.67 percent) were significantly different from the other segments, which ranged from 0.62 to 0.74 percent. Although the different yearly segments of wood and bark may contain large amounts of bark, particularly in the 1- and 2-year-old age classes, the volume of wood in these age classes is such that the overall ash content is fairly low.

Nutrient Analysis. Examination of selected segments of clone NE-388 indicate that accumulated concentrations of nutrients follow a function grouping--roots; wood and bark; bark; and 4-year-old leaves (Table 9). Roots (1- to 4-year-old) were significantly lower in concentrations of P, K, Ca, and Mg than those measured in all of the above ground parts. Wood and bark, and bark (1 to 4 years old) tissues were intermediate in accumulation of these mineral nutrients. Exception is the high concentration of Ca measured in the bark. Foliar tissues had the highest net concentration of accumulated nutrient levels.

Foliar nutrient concentrations measured in this study correspond to the values reported for field studies (Bowersox and Ward 1977, Voigt and others 1957, White and Carter 1970), but vary considerably from greenhouse sand culture studies (Bonner and Broadfoot 1967, Einspahr 1971) in concentration of macronutrients. Leaves are important sinks that when returned to the soil are valuable inputs to the nutrient cycle. Assuming that it requires 100 kg of leaves to produce 1,000 kg of wood and bark biomass and an annual productivity of 7.5 t/ha, four growing seasons would return 9.0 kg/ha of P, 65.1 kg/ha of K, 39.0 kg/ha of Ca, and 7.8 kg/ha to the biogeochemical cycle as litterfall.

Chemical Analysis. Total extractives can be divided into three significantly different groups: roots; 1- through 4-year-old wood and bark; and bark and leaves. The bark and leaves are three to four times higher in extractives than the other segments analyzed, whereas they are much lower in holocellulose and pentosans than the other segments. The holocellulose and pentosans were in general not significantly different in the other segments analyzed.

SUMMARY

The oven-dry gross heat of combustion and ash content between the seven clones is not significantly different. The nutrients and the chemical analysis showed some significant differences but these differences do not appear to change the gross heat of combustion and ash content. The nutrient depletions of the soil based on a yield of 30 t/ha of wood and bark removed from the site would be, on the average, 24 kg/ha of phosphorus, 105 kg/ha of potassium, 177 kg/ha of calcium, and 18 kg/ha of magnesium. These nutrients would probably have to be replaced by fertilizing and/or return of the ash after combustion.

The segmental analysis indicated that the oven-dry gross heat of combustion is not significantly different between the segments but the ash content, nutrient analysis and chemical analysis is significantly different between various groups of the segments, particularly the bark and leaves. Nutrient content and total extractive are much higher in the leaves than in the other segments analyzed. This indicates that the leaves should be left on site or their ash returned after combustion. If this is not done, nutrients will have to be added to the soil.

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APPENDIX G

DESIGN OF DEMONSTRATION WOOD-FIRED POWER PLANT

A. General

This appendix contains various details of the design of a wood-fired power plant which would be suitable to demonstrate the utility of solid fuel produced from an Energy PlantationTM subsystem of a PEF. The design is based upon available technology and off-the-shelf equipment. This guideline was adopted to keep down the cost of the demonstration power plant and to avoid the expense of doing research on combustion of wood, which is not viewed as the central purpose of demonstrating the PEF. For the purposes of investigating and developing improved combustion technology, a smaller plant than that envisioned for a demonstration PEF would be more suitable.

The power plant subsystem of a demonstration PEF is important and must be included; its purpose is to use the Energy PlantationTM fuel in a useful, reliable way as well as to supply the CO₂, ash, and waste heat to the algae pond. The power plant would also be used to demonstrate the wood-handling processes which are necessary to treat and to use wood fuel on a moderately large scale.

The next section of this appendix is a discussion of engineering considerations of air pollution control for the demonstration power plant.

Then a summary of the cost analysis and the equipment list is presented.

B. Air Pollution Control--Engineering Considerations

1. Regulation Considerations

We have established that at a boiler efficiency of 70 percent, about 1050 Energy PlantationTM acres are required to produce one megawatt of continuous electrical power. For the purposes of developing pollution control requirements and equipment, the following Energy PlantationTM sizes and corresponding continuous power output levels will be considered:

10500 acres	- - - - -	10 MW
21000 acres	- - - - -	20 MW
31500 acres	- - - - -	30 MW
63000 acres	- - - - -	60 MW

Particulate air pollution emission regulations applicable to plants of these sizes are presented in Table G-1. These data assume a boiler efficiency of 70 percent, a Rankine cycle (including turbine) efficiency of 28 percent and an electrical generator efficiency of 95 percent. For boilers whose input is greater than 250 million Btu per hour, the Federal New Sources Performance Standards are effective in all states, unless the state wishes to impose a stricter emission regulation.

Recently, a new federal regulation for air pollution control has become effective. This regulation (40CFR51), which is an interpretative ruling, essentially requires a firm that wishes to build a new facility or add to an existing one to implement a strategy to offset emissions from the new or added-to facility by reducing emissions elsewhere in the area by a greater amount, so that progress toward attainment of primary ambient air quality standards will be made. This ruling applies only to those (undefined) "areas" which are known, through monitoring, to be in violation of primary ambient air quality standards. The regulation is also only applicable to "major sources" which are defined as sources whose allowable

TABLE G-1

APPLICABLE PARTICULATE EMISSION REGULATIONS

(Allowable Pounds Per Million Btu Input)

Location	<u>Power Plant Size</u>			
	10 MW (183X10 ⁶ Btu/hr input)	20 MW (366X10 ⁶ Btu/hr input)	30 MW (549X10 ⁶ Btu/hr input)	60 MW (1098X10 ⁶ Btu/hr input)
All States, Federal New Source Performance Standards (NSPS)	N.A.	0.1	0.1	0.1
Alabama	0.14	0.1	0.1	0.1
Georgia	0.1	0.1	0.1	0.1
North Carolina	0.36	0.1	0.1	0.1
South Carolina	0.6	0.1	0.1	0.1
Virginia	0.1 or BACT* whichever least stringent	0.1	0.1	0.1

* Best Available Control Technology

Note: Assumption are 70% boiler efficiency, 28% Rankine cycle efficiency, 95% generator efficiency, and 6800 Btu/lb wet wood (at 20% moisture, and on which boiler efficiency is based), and 1200 Btu/lb steam

(after control) emission rate is 100 or more tons per year. This may be reduced to 50 tons per year. Any permits issued for construction of a source which are more lenient than allowed by the ruling fail to comply with the Clean Air Act.

2. Particulate Control Requirements

Consultants on this project report a wood-fired boiler emission factor of 34 lb particulates/ton wood burned. This factor is for operation of a stoker-fired boiler without flyash reinjection and a feed at 80 percent solids (including combustibles and ash). The Environmental Protection Agency reports values ranging from 25 to 30 lb/ton wood burned at 50 percent moisture. This range would correspond to 40-48 lb/ton wood burned at 80 percent moisture. These higher numbers are probably accounted for by the fact that EPA data were taken primarily from wood-waste boilers whose feed contains a greater fraction of high-ash bark than a PEF power plant feed. Additionally, all wood supplied to a PEF power plant will be milled and screened to remove a large fraction of ash, sand, and dirt. Thus we feel that 34 lb/ton of (80 percent solids) wood burned is a realistic and conservative emission factor for a PEF power plant boiler.

In order to compute the control requirements, we convert 34 lb/ton wood burned to a per unit Btu basis using 6800 Btu/lb wood. Thus the uncontrolled emission factor for a wood-fired boiler with no re-injection is about 2.5 lbs per million Btu input. Using this value, the percent control required to comply with applicable emission regulations is presented in Table G-2.

The regulations for North and South Carolina power plants at the 10 MW level are so weak that simple, medium-energy cyclones (2-3 in H_2O draft loss) would probably suffice. However, a power plant this size is very small from the electric utility point of view and represents the output of a fairly small Energy PlantationTM. Thus efforts for this work will be devoted to equipment selection, sizing, and costing for equipment to provide 96 percent control or better.

TABLE G-2

LEVEL OF PARTICULATE CONTROL REQUIRED TO COMPLY WITH APPLICABLE
EMISSION REGULATIONS

(Percent of uncontrolled value)

Location	<u>Power Plant Size</u>			
	10MW	20 MW	30 MW	60 MW
All states, Federal New Source Performance Standards (NSPS)	N.A.	96	96	96
Alabama	95	96	96	96
Georgia	96	96	96	96
North Carolina	86	96	96	96
South Carolina	76	96	96	96
Virginia	96 or BACT* whichever least stringent	96	96	96

* Best Available Control Technology

To gain insight into the level of difficulty presented by this control requirement, a sample calculation was carried out to determine the performance of a typical, large-diameter (6-foot) medium-energy cyclone operating with wood flyash. The cyclone performance parameters used in this example are reported in U.S. Environmental Protection Agency's Air Pollution Engineering Manual, AP-40, page 95, Figure 48. Using the basic data of example 18, page 97 of this reference, and the wood flyash size distribution shown in Figure G-1, a collection efficiency of 95 percent was obtained. Such a cyclone would typically present a pressure drop of 2-3 inches of water.

The efficiency computed in the example above is very high for a cyclone of its type. However, this high efficiency is accounted for by noticing that only 10 percent of the flyash is smaller than 50 microns in size. Cyclone efficiency for particles this size is better than 96 percent, in this example. It seems clear, then, that high-energy cyclones should easily collect better than 96 percent of the flyash, or possibly even medium-energy cyclones custom-designed for wood-ash properties.

3. Design of Air Pollution Control System for Demonstration Plant
Hunter Brooks, consultant on this project, suggests utilizing such medium-energy cyclones on flue gases exiting the boiler (see Figure G-2) as a first step in the particulate control strategy. These cyclones additionally serve to guarantee that no sparks are delivered to the chip dryers. These cyclones will remove 75-80 percent of the flue gas particulates, not a level sufficient to meet emission regulations.

The hot gases leaving this first set of cyclones are used to dry the wood chips. Wood chips are continuously loaded into a rotary dryer. The hot flue gases convey the chips through the dryer. The mixture of flue gases and chips exiting the dryer are pneumatically conveyed to a product cyclone, whose primary purpose is to separate the dried

Figure G-1: SIZE DISTRIBUTION OF WOOD FLYASH

Source: Battelle Columbus Labs, "Comparison of Fossil and Wood Fuels", March 1976, EPA-600/2-76-056

wood chips from the flue gases, and does not serve as a pollution control device. The gases exiting the product cyclone then contain small wood fibers and uncollected flyash.

To collect these fibers and flyash, Hunter Brooks has found from experience that Aerodyne dust collectors are very adequate for limiting emissions to less than 0.02 grains per standard cubic foot (SCF). Tests conducted at the Holly Hill, South Carolina, fiberboard operation showed an emission rate of 0.01 grains per SCF, well below the guaranteed limit. These emission rates can be compared with the emission regulations by noting that the volume of gas plus water vapor after the dryer is about 158 SCF per pound of as-burned wood. If the ash content of wood is 34 lb per ton of as-burned wood, the uncontrolled emission rate is 0.79 grains per SCF. Thus a controlled emission rate of 0.02 grains per SCF (assuming this is all flyash) indicates overall particulate control of 97 percent, well within the limits. Thus the control strategy proposed by Hunter Brooks is a sound, proven approach.

C. Design of Demonstration Wood-Fired Power Plant

Equipment lists and cost estimates were prepared for this potential demonstration power plant. Designs and estimates were prepared for three different sizes of power plants: (1) a 30-MW plant utilizing two 15-MW boilers, (2) a 45-MW plant utilizing three 15-MW boilers, and (3) a 60-MW plant utilizing four 15-MW boilers. Tables G-3 through G-10 present design estimates for these three cases, a breakdown of nonfuel operating expenses, and summary equipment lists.

TABLE G-3

**PRELIMINARY DESIGN ESTIMATE
CASE NO. 1 TWO BOILERS**

	<u>Equipment Cost</u>	<u>Installed Cost Total</u>
Civil Work and Site Work 50 Acres		\$ 1,450,000
Architectual Work		2,600,000
Structural Work		4,000,000
Process Structural		900,000
HVAC (Building)		600,000
Plumbing		250,000
Shop Equipment		<u>35,000</u>
Sub-Total Building Cost		\$ 9,835,000
AREA 01 COMMON EQUIPMENT		
Equipment @ 15%	\$ 2,634,000	3,029,000
Electrical @ \$120/HP	3826 HP	459,000
AREA 02 FUEL TRAIN		
Equipment @ 15%	3,292,000	3,786,000
Electrical @ \$120/HP	6266 HP	752,000
AREA 03 FINES FUEL TRAIN		
Equipment @ 15%	530,000	610,000
Electrical @ \$120/HP	1172 HP	129,000
AREA 04 BOILER AND GENERATOR		
McBurney Quote (Non-Union)		14,500,000
Equipment @ 15%	398,000	458,000
Electrical @ \$120/HP	1620 HP	196,000
Fire Protection (Water)		800,000
Process Piping		1,000,000
Misc. Electrical		<u>500,000</u>
Total		\$16,054,000
Contingency @ 10%		<u>3,605,000</u>
TOTAL		\$19,659,000

TABLE G-4

**PRELIMINARY DESIGN ESTIMATE
CASE NO. 2 THREE BOILERS**

	<u>Equipment Cost</u>	<u>Installed Cost Total</u>
Civil Work and Site Work 50 Acres		\$ 1,450,000
Architectual Work		2,600,000
Structural Work		4,000,000
Process Structural		900,000
HVAC (Building)		600,000
Plumbing		250,000
Shop Equipment		<u>35,000</u>
Sub-Total Building Cost		\$ 9,835,000
AREA 01 COMMON EQUIPMENT		
Equipment @ 15%	\$ 2,634,000	3,029,000
Electrical @ \$120/HP	3826 HP	459,000
AREA 02 FUAL TRAIN		
Equipment @ 15%	4,938,000	5,679,000
Electrical @ \$120/HP	9399 HP	1,128,000
AREA 03 FINES FUEL TRAIN		
Equipment @ 15%	795,000	914,000
Electrical @ \$120/HP	1175 HP	211,000
AREA 04 BOILER AND GENERATOR		
McBurney Quote (Non-Union)		21,000,000
Electrical @ \$120/HP	2445 HP	293,000
Fire Protection (Water)		800,000
Process Piping		1,000,000
Misc. Electrical		<u>500,000</u>
Total		\$44,848,000
Contingency @ 10%		<u>4,485,000</u>
TOTAL		\$49,333,000

TABLE G-5

**PRELIMINARY DESIGN ESTIMATE
CASE NO. 3 FOUR BOILERS**

	<u>Equipment Cost</u>	<u>Installed Cost Total</u>
Civil Work and Site Work 50 Acres		\$ 1,450,000
Architectual Work		2,600,000
Structural Work		4,000,000
Process Structural		900,000
HVAC (Building)		600,000
Plumbing		250,000
Shop Equipment		<u>35,000</u>
Sub-Total Building Cost		\$ 9,835,000
AREA 01 COMMON EQUIPMENT		
Equipment @ 15%	\$ 2,634,000	3,029,000
Electrical @ \$120/HP	3826 HP	459,000
AREA 02 FUEL TRAIN		
Equipment @ 15%	6,584,000	7,572,000
Electrical @ \$120/HP	12532 HP	1,504,000
AREA 03 FINES FUEL TRAIN		
Equipment @ 15%	1,060,000	1,219,000
Electrical @ \$120/HP	2344 HP	281,000
AREA 04 BOILER AND GENERATOR (McBurney Quote (Non-Union))		28,000,000
Equipment @ 15%	796,000	915,000
Electrical @ \$120/HP	3260 HP	391,000
Fire Protection (Water)		800,000
Process Piping		1,000,000
Misc. Electrical		<u>500,000</u>
Total		\$55,505,000
Contingency @ 10%		<u>5,505,000</u>
TOTAL		\$61,010,000

TABLE G-6

NON-FUEL OPERATING EXPENSES

Steam Generation Power Generation	300,000 #/Hr. 30 MW	450,000 #/Hr. 45 MW	600,000 #/Hr. 60 MW
Payroll:			
Administration	\$ 179,000	\$ 179,000	\$ 179,000
Direct Labor	359,000	404,000	538,000
Fringe Benefits	201,000	218,000	268,000
Total Payroll	<u>739,000</u>	<u>801,000</u>	<u>985,000</u>
Depreciation (30 yr. st. line)	1,322,000	1,644,000	2,034,000
Water Pollution Control	95,000	113,000	122,000
Insurance:			
Boiler	2,500	4,000	5,000
Fire & Extended Coverage	24,000	29,000	34,000
Water	140,000	210,000	280,000
Chemicals	212,000	319,000	425,000
Ash Disposal	207,000	310,000	413,000
Main. & Repairs	<u>940,000</u>	<u>1,330,000</u>	<u>1,700,000</u>
Yearly Non-Fuel Cost	3,681,500	4,760,000	5,998,000
Operating Hrs/Yr. @ 85%	7,446	7,446	7,446
KW Hrs/Year	223,380,000	335,070,000	446,760,000
Non-Fuel Cost/KWH	\$0.0165	\$0.0143	\$0.0134
Tons Fuel/Hr. O.D.	32.8	49.2	65.6
Fuel Cost/Ton O.D.	20.00	20.00	20.00
Fuel Cost/Year	4,885,000	7,327,000	9,769,000
Fuel Cost/KWH	0.0219	0.0219	0.0219
Total Power Cost	0.0389	0.0366	0.0354
Connected HP Est.	19,438	29,157	38,876
Connected KWH	14,481	21,722	28,966
@ 60% Usage	8,689	13,033	17,379
KWH/Year Used In-House	64,600,000	97,044,000	129,397,000
Percent of Total	29%	29%	29%

TABLE G-7

EQUIPMENT LIST SUMMARY

AREA 01 - EQUIPMENT COMMON TO ALL BOILERS

<u>Equipment No.</u>	<u>Description</u>	<u>Total HP</u>	<u>Estimated Equip. Cost</u>
01-01	Truck Scale	3 KW	50,000
01-02	Trailers Side Dump (75 Req.)		1,508,000
01-03	Truck Dumper Conventional	50	75,000
01-04	Hopper Receiving	75	85,000
01-05	Truck Dumper Side Unload	80	53,000
01-06	Hopper Receiving	75	63,000
01-07	Conveyor Belt	65	120,000
01-08	Magnet (Metal Removal)	4 KW	5,000
01-09	Pneumatic Conv. Pile Builder	2000	275,000
01-10	Wet Storage		
01-11	Chip Reclaim	35	38,000
01-12	Pneumatic Conv. to Silos	1350	180,000
01-13	Bark Silo Special		92,000
01-14	Roto-Centric Unloader	100	80,000
01-15	Conveyor Silo Outfeed	5	5,000
01-16	Magnet (Metal Removal)	4 KW	5,000
	TOTALS	3826	\$2,634,000

TABLE G-8

EQUIPMENT LIST SUMMARY

AREA 02 - BOILER A RELATED FUEL TRAIN

Note: Boiler B, C, and D would require identical equipment

<u>Equipment No.</u>	<u>Description</u>	<u>Total HP</u>	<u>Estimated Equip. Cost</u>
02-01	Silo Wet Chip (86,000 Ft ³)		92,000
02-02	Roto-Centric Unloader	75	80,000
02-03	Conveyor Silo Outfeed	5	5,000
02-04	Ray-Weigh Guage on 02-03		7,000
02-05	Magnet (Metal Removal)	4 KW	5,000
02-06	Moisture		10,000
02-07	Hammermill	600	71,000
02-08	Conveyor Inclined Screw	7.5	4,000
02-09	Pneumatic System High Pressure	500	195,000
02-10	Drier No. 1 Surge Feeder	8	293,000
02-11	Conveyor, Horizontal Screw	7.5	5,000
02-12	Drier No. 1 Rotary Hell	225	Incl.
02-13	Conveyor, Outfeed Screw	7.5	5,000
02-14	Drier No. 2 Surge Feeder	8	Incl.
02-15	Conveyor, Horizontal Screw	7.5	5,000
02-16	Drier No. 2 Rotary Hell	225	Incl.
02-17	Conveyor, Inclined Belt	3	5,000
02-18	Moisture Gage		10,000
02-19	KMW Chip Screen	10	45,000
02-20	KMW Equalizing Bin		25,000
02-21	Pneumatic System Accepts	500	195,000
02-22	Silo Dry Chip (86,000 Ft ³)		92,000
02-23	Roto-Centric Unloader	75	69,000
02-24	Conveyor Silo Outfeed	5	5,000
02-25	Magnet (Metal Removal)	4 KW	5,000
02-26	Ray-Weigh Guage on 02-24		7,000
02-27	Moisture Meter		10,000
02-28	Pneumatic Conveyor Boiler Feed	800	160,000
02-29	Bin Vent Dry Chip Silo	55.5	25,000
	TOTALS	3132.5	\$1,646,000

TABLE G-9

EQUIPMENT LIST SUMMARY

AREA 03 - CHIP FINES FUEL SYSTEM

(Receiving chip fines minus 1/8" fraction from Screen 02-19)

<u>Equipment No.</u>	<u>Description</u>	<u>Total HP</u>	<u>Estimated Equip. Cost</u>
03-01	Pneumatic Conveyor Chip Fines	73	50,000
03-02	Filter Clarke	15.25	25,000
03-03	Silo Chip Fines Fuel (86,000 Ft ³)		92,000
03-04	Roto-Centric Unloader	75	69,000
03-05	Conveyor Silo Outfeed	5	5,000
03-06	Ray-Weigh Guage on Conveyor 03-05		7,000
03-07	Magnet (Metal Removal)	4 KW	5,000
03-08	Moisture Meter		10,000
03-09	Pants Leg Flow Splitter		2,000
03-10	Bin Metering to Drier #1	5	Inc. in Drier Price
03-11	Pneumatic Conveyor Burner #1	50	"
03-12	Coen Burner #1	2	"
03-13	Combustion Blower #1	150	"
03-14	Plenum to Drier #1 Furnace		"
03-15	Bin Metering to Drier #2	5	"
03-16	Pneumatic Conveyor Burner #2	50	"
03-17	Coen Burner #2	2	"
03-18	Combustion Blower #2	150	"
03-19	Plenum to Drier #2 Furnace		"
	TOTALS	586.25	\$265,000

TABLE G-10

EQUIPMENT LIST SUMMARY

AREA 04 - BOILER, GENERATOR AND RELATED EQUIPMENT

(McBurney Supply Non-Union)

<u>Equipment No.</u>	<u>Description</u>	<u>Total HP</u>	<u>Estimated Equip. Cost</u>
04-01	Feeder Pulsating Bark	1	4,500,000
04-02	Chip Feeder #1	5	Incl.
04-03	Chip Feeder #2	5	"
04-04	Chip Feeder #3	5	"
04-05	Chip Feeder #4	5	"
04-06	Chip Feeder #5	5	"
04-07	Conveyor Chip Infeed	10	"
04-08	Boiler MKB Water Tube		"
04-09	Air Pre-Heater		"
04-10	Fan I.D.	700	"
04-11	Fan F.D.	100	"
04-12	Fan O.F.	60	"
04-13	Dust Collector	2	"
04-14	Screw Conveyor	11	"
04-15	Ajax Classifier	5	"
04-16	Fan Fly Ash Re-Inj.	5	"
04-17	Screw Conveyor Sand	5	"
04-18	Screw Conveyor Ash	5	"
04-19	Water Softening System		"
04-20	Soft Water Storage #1		"
04-21	Soft Water Storage #2		"
04-22	Soft Water Pump #1	15	"
04-23	Soft Water Pump #2	15	"
04-24	Deaerator		"
04-25	Pump, Boiler Feed #1	150	"
04-26	Pump, Boiler Feed #2	Steam	"
04-27	Combustion Controls		"
04-28	Air Compressor	250	"
04-29	15 MW Generator		2,500,000
04-30	Flue Gas Plenum from Boiler to Rotary Driers		Incl.
04-31	Dust Collector Aerodyne #1	356	133,000
04-32	Conveyor Dust Away #1	15	8,000
04-33	Dust Collector Aerodyne #2	356	Incl.
04-34	Conveyor Dust Away #2	15	8,000
04-35	Pneumatic Conveyor: Dust Common	73	50,000
04-36	Fenwall Explosion Protection Equip.		250,000
	TOTALS - Installed	*2174	\$ 7,250,000
	Not Installed		199,000

*815 HP not supplied and installed by McBurney

APPENDIX H

FINAL REPORT

DESIGN OF THE ALGAL POND SUBSYSTEM OF THE PHOTOSYNTHESIS ENERGY FACTORY

BY

J.R. Benemann
B.L. Koopman
D.C. Baker
R.P. Goebel
W.J. Oswald

Sanitary Engineering Research Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

The concept of the Photosynthesis Energy Factory (PEF) involves a combined and synergistic operation of an Energy PlantationTM (EPTM) and an algal pond system. The EPTM cultivating short-rotation hardwoods would primarily produce boiler fuel for electricity generation and the algal ponds biomass suitable for digestion to methane. The analysis of the optimal synergism based on existing knowledge and data indicates the feasibility of using locally available waste flows for algal production in ponds to supply a significant fraction of the nitrogenous fertilizer and irrigation water required by an EPTM. A design of an algal pond subsystem of a PEF is presented based on a 5 MGD waste flow (50,000 people) and several specific site, design, and operational assumptions. A conventional primary treatment design was used.

The design assumes that algal biomass (containing 8% N) is grown to 80% of the theoretical N growth potential of the liquid waste (assuming a relatively high N content of 65 mg/l). Carbon dioxide from power plant flue gas provides the additional C requirement for growing the algae past the C content of waste (about 12,000-16,000 lbs carbon dioxide required/day). From the diffusion constants of carbon dioxide in water, carbonation of the ponds does not appear to present a significant problem. At an assumed conversion efficiency of 2.7% of photosynthetically available solar radiation (which varies from 2.2% in summer to 3.2% in winter), a total of twelve, 30-acre high-rate ponds will be required for a 5 MGD waste flow (of which only eight need to be operated in summer). Algal detention times vary from six to nine days and microstrainer harvestabilities from 75% in winter to 85% in summer. Between seven and ten tons of algae are harvested/day by twelve large microstrainers (rated total capacity 15 MGD). Final algal concentration (to 2-5% volatile suspended solids) is accomplished by two, one-half acre settling ponds. Reclaimed water (from 2.74 MGD in May to 5.65 MGD in November) is stored in three, 10-acre (5 MGD) isolation ponds which also serve to remove remaining algae from effluents.

The design assumes conventional primary treatment and anaerobic digestion systems (total annual costs \$282,000). The 400-acre pond system is cost estimated at \$200,000/year and harvesting costs at \$300,000/year. These costs are competitive with conventional waste treatment. Indeed, the design assumptions chosen were the minimum required to allow a favorable cost comparison. Energy outputs exceed inputs by a factor of two if waste treatment, water reclamation, and fertilizer are considered together with digester methane as outputs.

The pond design and operational assumptions (solar conversion efficiencies, harvestabilities, etc.) need to be tested at the pilot pond (about one acre) scale. The critical assumptions are the mixing and carbonation systems, algal growth parameters and yields, and reliability of the proposed harvesting system.

Considerable improvements and/or cost restrictions of the pond systems should be possible if any of several technological advances can be achieved (e.g. improved photosynthetic efficiencies, tertiary waste treatment with nitrogen-fixing blue-green algae, algal harvesting by sedimentation or flotation, etc.)

Although the relative size of EPTM to algal ponds will vary, ratios of about 10:1 appear optimal where rainfall limits the scale of the EPTM. Indeed, in this range of ratios, cash flows generated by algal ponds could subsidize the EPTM operations, allowing for modest scales. Thus, the PEF would be able to function beyond the normal geographical and economic limitations of the EPTM alone. Integration of the PEF concept into a generalized bioconversion system, utilizing available forest, agricultural, and urban wastes, would allow biomass to supply a significant fraction of local fuel requirements.

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The Energy Plantation (abbreviated EP) is a trademark of the InterTechnology/Solar Corp. The concept of the Photosynthetic Energy Factory was devised jointly by Drs. W.J. Oswald and G.C. Szego.

NOTICE

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I. INTRODUCTION

PROJECT DESCRIPTION

The Photosynthetic Energy Factory concept involves the integrated operation of an "Energy Plantation" (trademark of the InterTechnology/Solar Corp.) and a microalgal pond system. The Energy PlantationTM (EPTM) is a concept (1, 2) that encompasses the intensive production of woody plants, specifically of short rotation hardwoods, which can be cultivated through coppicing (growth from cut stumps). Algal ponds have been developed as a method of sewage treatment (3-6) and microalgae were among the earliest "fuel crops" proposed (7, 8).

No specific technical limitations to silviculture biomass plantations exists. If presently assumed yields and cultivation requirements are correct, biomass production costs in the range of \$1/MBTU to maximally \$2/MBTU could be achieved (2, 9, 10). This would be a competitive fuel price in many localities. Algal ponds are large, shallow (about one foot deep) channelized ponds which have been used for sewage treatment as well as, to a limited extent, microalgal production. The limitations of microalgal biomass production are primarily technical: low-cost harvesting and cultivation systems are not yet developed.

Algal pond and Energy PlantationsTM have complementary advantages and disadvantages which result in significant synergism in systems incorporating both concepts. For example, dry land Energy Plantations can effectively store the collected solar energy; an algal pond system is limited to a few days storage. Another example of complementarity is the difference in biomass produced: the dry biomass from the Energy Plantation is a most suitable fuel for electricity production while the wet non-cellulosic biomass

of microalgae is most suited for methane fermentations. Use of new irrigation water may be prohibitively costly for energy plantations, severely restricting their range. However, using reclaimed water from algal ponds might allow economical irrigation of energy plantations. The two systems have different requirements for land. Algal ponds require flat land while energy plantations could be established on relatively steep slopes. Fertilizer produced by the algal ponds might be used for energy plantations while the carbon dioxide from the power plant subsystem of the EPTM is an essential nutrient for the algae.

The general purpose of this project was to determine how well the objectives of an integrated PEF based on AP and EPTM could be achieved with present, state-of-the-art engineering and minimal extrapolations of experimental data.

The specific objectives contemplated under this subcontract project were (1) the development of the PEF concept and an engineering analysis of the algal pond subsystem of the PEF; and (2) the design of an algal pond pilot plant and operations which would test the operational assumptions presently required for the engineering analysis. These objectives have been achieved to a substantial degree.

The present technical development of algal pond systems do not yet allow the design of a PEF which utilizes the full potential of algal cultivation. For example, the use of nitrogen-fixing blue-green algae for large-scale production of fertilizer (and tertiary waste treatment) has only recently been established at the experimental pond level (11). The requirement for using available technology (or technology that is ready to be tested at the pilot scale) in development of the PEF thus did not allow specification of blue-green algae for pond operations.

A review of available engineering and economic facts for microalgal

ponds (12-16) reveals microalgal harvesting as the key technical problem. A solution to this problem has recently been investigated with experimental sewage ponds (3 and 12 m²) which have been operated under conditions which allow algal harvesting with microstrainers (17, 18). On the basis of these data, assumptions have been formulated which allowed the design for the AP subsystem of the PEF presented here. The test of these design assumptions or equivalent ones is necessary before this algal cultivation technology can be used in bioconversion.

BACKGROUND NARRATIVE

Bioconversion--the production of energy from biomass--is becoming an important part of the future energy plans for the United States. There are considerable amounts of biomass available in urban forestry and agricultural wastes and their residues. Their utilization for conversion to fuel could help solve a major environmental problem (waste disposal) and contribute about 5% of present U.S. energy requirements (19). Increasing fuels from biomass above that recoverable from wastes or residues will require specifically growing biomass for energy production. The requirements of biomass production for energy are: high photosynthetic efficiencies, low capital and operational costs (particularly in irrigation and fertilization), and utilization of land or water unsuitable for agriculture or other higher uses.

The requirements for land are high--100 million acres (5% of continental U.S. land area) at an overall 1% solar conversion efficiency could only supply one-third of the present energy requirements of the United States. This would increase the acreage under cultivation by about 25%, a very major undertaking. Considering the energy, water, and environmental problems already faced in modern agriculture, present farming practices and techniques cannot be utilized effectively in energy farming. Energy farming necessitates new types of crops specifically adapted for maximization of solar energy

conversion into an easily harvested plant material which can be efficiently used as, or converted into, fuel. The cost of planting and maintaining energy crop plants must be low and these energy crop plants should preferably be capable of year-round growth and yield, require only minimum wastewater and fertilizer input, and be grown under conditions allowing multiple land use.

Biomass production systems could have a potentially important role in waste treatment and nutrient recycling. One example is in the disposal of sewage sludge. After digestion (to yield methane gas) the stabilized sludge still contains infectious and toxic agents (particularly heavy metals) which limit its desirability in agricultural applications. Its soil conditioning characteristics, however, would make it well suited for application to the marginal lands likely to be used in energy farming where potential toxic substances would have only minimal health impacts. The costs of alternative methods of sludge disposal, together with EPA policy favoring land application, suggests biomass production systems as ideal candidates for sludge disposal. The nutrient content of digested sewage sludge could be a significant factor in the operation of an EPTM.

Sewage and other liquid wastes could also be disposed of directly on "fuel farms," including the silviculture Energy PlantationTM. Sewage disposal on land, including forest stands, has been practiced in a number of localities (20). However, it appears preferable in most, if not all, cases to use algal ponds for prior treatment of the sewage. There are several reasons for this: (1) the use of raw sewage in irrigation acidifies the root zone and leads to anaerobic conditions and excessive bacterial and fungal growth; (2) The sewage tends to clog the soil, resulting in excessive runoff; (3) The requirements for irrigation and fertilization are not matched by the sewage flows or compositions and are different during the year. Algal pond treatment would allow production of an algal fertilizer

of high quality as well as a treated sewage effluent, both of which can be stored; (4) The algal pond system could be more productive in terms of biomass yields than the EPTM; (5) The methane produced by the algal pond might be more desirable than the solid fuel produced by the energy plantation; (6) The algal pond could be located closer to the population centers, permitting distribution of the pond effluent through open channels (rather than the more expensive sewage pipes) to the EPTM. These reasons, although not universally applicable to all locations and situations, are sufficient to consider a PEF system comprised of both algal ponds and silviculture Energy PlantationsTM rather than direct wastewater use in the EPTM.

The concept of the PEF is only one example of integrated multipurpose bioconversion systems. Use of marsh systems and other types of multiplant communities of fast-growing successive species offers the potential of high productivities with minimum management inputs. The quality requirements of biomass usable for conversion to fuels are relatively minimal, allowing simultaneous cultivation of a number of different plants. Thus, monocultures are not strictly necessary as they are in conventional agriculture. As monocultures do not minimize cultivation inputs or loss of productivity due to disease, pests, etc., they should be avoided in biomass production. Thus, the concept of cultivation of single-specie stands of hardwoods or a uni-algal culture in ponds will, undoubtedly, be less preferable to that of multi-specie systems.

Land reclamation is another function that can be filled by bioconversion systems. In modern agriculture and other activities, many millions of acres of land have been ecologically destroyed by man. These could be reclaimed and made usable through a program which uses waste disposal (sludge, composting, liquid wastes, etc.) combined with appropriate biomass production (either terrestrial and aquatic) to result, after a number of years, in land suitable for higher purposes.

Biomass-energy systems will comprise a set of alternative technologies based on a multiplicity of plants (terrestrial and aquatic) adapted to various climates. This will allow adaptations of such systems to the most diverse environments, covering wide ranges of insolation, precipitation, temperature, etc. An important aspect of biomass production systems is their integration into the existing ecological and environmental setting. Multiple land use will require compatibility with wildlife management and recreational activities. Preservation of open spaces and habitat protection must be considered in the development of biomass systems. Indeed, such ancillary functions might provide an economic incentive during the early stages of the development of photosynthesis energy factories; waste disposal could be a more important, in the short-term, economic factor than the net fuel produced by these systems. This can shorten development times for operational systems and allow a gradual increase in system size and energy production as technology is perfected and fossil energy resources diminish. Thus, such systems will be initially limited in size by a number of constraints dictated primarily by the needs of waste treatment and other ancillary functions listed. These limitations in size are a general phenomenon of bioconversion systems. The constraints on size of PEF's include the need to be located near urban areas (the source of sewage), the availability of land, the transportation costs of biomass, the markets for the fuels, etc. Such size constraints will require an appropriately scaled conversion technology for the biomass produced. This is a key consideration, suggesting that, for the immediate future, combustion and digestion will be the preferred alternatives. (On a longer range, conversion of biomass to liquid fuels could become significant.)

Early operation of commercially successful biomass production and conversion systems is an urgent task. Although such operations would have little immediate impact on the national energy picture, until perhaps after

the end of this century, successful bioconversion systems would focus attention on the potential benefits of this approach to local and regional energy supply problems. It would also hasten research and development into large-scale bioconversion systems, make available the necessary capital required for initiating new projects, and generally speed up the evolution and adoption of the energy alternative presented under the broad heading of bioconversion. Achievement of a self-sustained operation requires the demonstration of its technical and economic feasibility at the pilot plant level.

PROJECT SUMMARY

The size of the algal pond subsystem of the PEF is limited by the available sewage flows. Very large urban areas will be limited in applications of PEF's by suitable land availability. In the analysis of the PEF carried out by the InterTechnology/Solar Corp. (2), the algal waste treatment ponds represented waste flows from generally small localities located near the sites of large, available tracts of suitable land. Furthermore, algal cultivation was carried out only to the C limiting algal growth potential of the sewage, resulting in effective waste treatment but making no use of the carbon dioxide from the power plant nor maximizing N fertilizer recycling. Thus, in the ITC study, the percentage land area of the algal pond extended from less than 0.1% to maximally 1.5% of the total PEF land area at any of 15 potential PEF demonstration sites. These sites were located all in areas where rainfall would allow operation of the EPTM on natural rainfall, thus not making use of the water reclamation potential of the algal waste treatment system. If the assumption was made that nitrogen-fixing blue-green algae could be cultivated, then the size of the algal ponds increased almost eight-fold (2), although the overall percentage is still relatively low. A more detailed discussion of the InterTechnology/Solar Report is given in Chapter X.

The design presented below assumed that the algae would be grown to the N growth potential. This avoids an assumption about the cultivation of blue-green algae while increasing N fertilizer values as well as utilization of some of the carbon dioxide derived from the Energy PlantationTM. The design of the algal pond system differed substantially from the InterTechnology/Solar Corp. design; nevertheless, it can be concluded from both designs that algal pond technology need only establish modest improvements in state of the art and economics to be a viable option in bioconversion integrated with sewage treatment. The algal pond design presented here is not parametric: a single case (a 5 MGD sewage flow in the southwest) was analyzed in detail. However, simple substitutions of design factors allows ready determination of the sensitivity of the system to various changes in assumptions (see Chapter IX). An analysis was also performed on the best match-up of an algal pond using this design and an Energy PlantationTM.

A relatively small Energy Plantation, about 10 times (5-20 range) the size of the algal pond system, (about 400 acres) is optimally scaled. It would utilize all the effluent water of the sewage pond system and absorbing all the nutrients and sludge (primary and algae) generated. The daily output of the PEF would be about 100 MBTU/methane (as medium BTU SNG) and 200 to 800 MBTU of wood fuel (depending on the size and productivity of the Energy PlantationTM). The urban solid wastes generated by the community of 50,000 is about equal in fuel value to the maximal outputs of such a PEF, while the rurally available forestry or agricultural wastes and residues could, in many cases, double total output again, to result in a bioconversion system with a yearly average output of approximately 3,000 MBTU of fuel/day, or approximately 5% of total U.S. per capita fuel consumption. Combining all the solid biomass fuels would allow operation of reasonably sized conversion systems in the range of 200 tons/day. Light industrial-commercial utilization

of this fuel resource would be a preferable route due to uncertainties in present and foreseeable fuel allocation systems, relative economic impacts, and ability to adjust to these types of fuel supplies. The basic concept is shown in Figure 1 and discussed in more detail in the last chapter. This approach to bioconversion systems, as opposed to the very large-scale centralized systems of a hundred square miles for algal ponds (21) or tens of thousands of acres for silviculture biomass farms (9, 10) and Energy PlantationsTM, is favored by the realities of present-day economics, land use patterns, technical state of the art, and environmental acceptability.

Even if "dedicated" energy plantations are established for fuel production, they would be indirectly subsidized by the higher pulp-paper prices occasioned by reduced supply. Only if that market is satisfied can large-scale hardwood production develop and expand to supply a larger fraction of the local fuel requirements. This could undoubtedly take place in the longer term future. Until then, smaller-scale integrated biomass systems will be favored. Such integrated systems may be multipurpose forests which provide both pulp and fuel in an overall optimized production unit.

FIGURE 1. INTEGRATION OF ENERGY-WATER-WASTES-BIOMASS FLOWS.

II. ALGAL POND SUBSYSTEM OF THE PEF

Liquid waste treatment in large lagoons or oxidation ponds is an established technology which has found widespread application in the U.S. and abroad. The oxygen required for waste degradation is provided by the photosynthetic activity of microalgae in the ponds. This process of "photosynthetic oxygenation" is the least expensive method of sewage and liquid waste treatment wherever land costs are not prohibitive. The theory and practice of oxidation ponds has been the subject of extensive studies (22,23).

Facultative ponds--the predominant type in use today--are relatively deep (5 to 8 feet) and commonly receive raw sewage. Because of their depth and the absence of mixing, algal concentrations obtained in facultative ponds tend to be relatively low. "High-rate" ponds, which incorporate shallower depths and mechanical mixing, produce higher algal concentrations but require pretreatment of the influent sewage to remove settleable solids. This latter type of pond must be used if algal production is to be maximized. The general engineering aspects of microalgal pond design and operations are discussed in detail in Reference (12). The potential role of such sewage treatment systems in energy production has been reviewed repeatedly (17,18). These should be consulted for discussion of the technical background to this report.

Several high-rate ponds have been designed and operated, including a pilot algal production plant (0.65 acre) at the Sanitary Engineering Research Laboratory, Richmond, California; a relatively deep pond system at Modesto, California (850 acres); and an integrated facultative and high-rate pond at St. Helena, California (15 acres). Presently, a medium-scale, high-rate oxidation pond is being designed for Hollister, California. Thus, high-rate

algal ponds are a technology which can be applied to the purpose of the PEF. However, operational data on algal productivity over extended periods of time in high-rate ponds are not available.

Up to now, oxidation ponds have been designed and operated to maximize waste treatment effectiveness, not biomass production. Indeed, in present oxidation ponds, the algae grown are either carried off in the pond effluents or settle to the bottom of the ponds. The former is of concern since it can lead to accelerated eutrophication. In the latter case, the algal biomass is lost for bioconversion purposes.

Harvesting of the microalgae produced in oxidation ponds has long been recognized as an important goal which could achieve the dual aim of advanced waste treatment and large-scale production of algal biomass convertible into methane. Technology of algae harvesting is limited by: (1) the small size of most algae produced in ponds; (2) the diversity of algae species and their complex population dynamics. Because of this, filtration and sedimentation have thus far met with only sporadic and limited success. Present methods, being applied to several large pond systems, utilize chemical flocculation followed by sedimentation or flotation as the key element in the algae harvesting process. This, however, results in an algae-chemical mixture which may be unsuitable for further processing. Anyway, these harvesting processes are expensive.

Work is being carried out on physical-chemical methods of oxidation pond algal separations including ultrafiltration, magnetic separation, polymeric flocculents, etc. Preliminary cost analysis indicates that these have little economic advantage. One different approach to the problem is to grow specific algal strains in oxidation ponds which can be readily harvested because of their size or sedimentation properties. Algal species control permitting economical harvesting is probably a prerequisite for any large-scale intensive algal biomass production system. This subject is extensively covered in recent

reports (17,18) and papers (24,25). Briefly, microstraining or settling are the least expensive harvesting methods and also the most species dependent. The use of microstraining is allowable economically in waste treatment systems and thus is applicable to the requirements of the PEF.

Severe limitations exist at present in the development of a PEF design, particularly in the lack of experience in operation of large-scale freshwater microalgal bioconversion systems based on nitrogen-fixing blue-green algae (11). Since the requirements for development of a PEF system dictated use of presently available information and designs, it is not possible to fulfill the original aims of the PEF until further research and development have demonstrated the feasibility of large-scale freshwater microalgal systems based on blue-green algae. It appears, however, possible to design an algal pond subsystem which fulfills the key requirements of fertilizer and reclaimed water supply to the Energy Plantation.TM In practice this can be accomplished using a conventional high-rate pond system in which algae are grown to the N growth potential of the influent wastes, harvested, digested, with the digested sludge applied to the Energy Plantation.TM Such a design is based on recent experiments in developing high-rate pond operations which allow cultivation of algal biomass that can be efficiently harvested by microstrainers (18).

The design of an Algal Pond Subsystem detailed in the next chapters allows the provision of a substantial portion of the fertilizer required by the Energy Plantation,TM as well as sufficient reclaimed water to allow a significant geographical extension of the Energy PlantationTM beyond present limits dictated by mean annual rainfalls.

There are presently many unknowns involved in the operations of the Energy PlantationTM subsystem of the PEF. The methods of sludge application, fertilization, and irrigation have not yet been defined. For the purposes

of this preliminary design of the algal pond subsystem, as few assumptions as possible were made regarding the interrelationships of the algal pond and Energy PlantationTM subsystems. These are shown diagrammatically in Figure 2; quantification of the interrelationships is attempted in Chapter X.

FIGURE 2. THE PHOTOSYNTHESIS ENERGY FACTORY

III. POND DESIGN AND SITING ASSUMPTIONS

The objective of the algal pond is to supply fertilizer and reclaimed wastewater to the EPTM subsystem using locally available liquid wastes. Although at present 170 lbs of N/acre-year and only natural rainfall is specified for the EPTM (2), the design of the algal pond is generalized to provide maximum N fertilizer and as much reclaimed water as possible. The assumptions made in the design of the algal pond are conservative with only low-cost algal harvesting and N recovery as major design innovations. A major effort in choosing design assumptions was to reduce the differential between winter and summer months in pond size required. Designs based on the worst winter months result in excess capacity during the summer; alternately, designs for average conditions must provide for storage of winter flows.

The key design assumptions are: 80% harvestability of algae by micro-straining, 80% of input sewage N recovered in the algal biomass, and a gross 1.5% yearly average total solar conversion efficiency by the algae.

This preliminary design presents the basic formulae and design specifications, format, and data sheets for the calculations using a sample design based on a 50,000 people-equivalent waste flow. The cost estimates are based on EPA cost estimates, updated contractors' costs for existing oxidation ponds, manufacturers' data, and approximations for particular unknowns. Engineering designs and specifications are not provided in detail for conventional components of the algal pond subsystem (e.g. the sewer connections, pumping station, settling chamber, and conventional digesters).

Siting the PEF will require different criteria than those for the Energy PlantationTM or the Algal Pond System operating separately. The main

objective of the PEF project is to demonstrate, if possible, that a synergism exists between dry land and aquatic biomass production for bioconversion purposes. Although the effort is designed to specifically test (through an engineering analysis, a preliminary design, and site selection) the PEF concept for the Energy PlantationTM and Algal Pond Systems, the general PEF idea is much broader and could find applications in any of the combinations of dry and aquatic biomass production systems. Indeed, the unique aspect of this project is that it is the first attempt to develop a bioconversion system based on the integration of two distinct plant types and cultivation technologies. This is the likely direction that bioconversion is bound to take in the future; dependence on the rigid patterns of large-scale monocultures found in modern agriculture cannot be cost effective in the production of biomass for conversion to fuels.

In site selection particular emphasis should be placed on the need to demonstrate synergism between the EPTM and AP subsystems. Thus, all areas where algal ponds are not feasible due to low insolation, low waste flows, or low temperatures must be avoided. The ideal site is one that is marginal or infeasible for the EPTM alone but suitable for the integrated PEF system. In Table 1 are given the general site selection considerations and identifiable parameters for the algal pond subsystem of the PEF.

In Table 2 are listed the parameters assumed for the site selected for the algal ponds of the PEF. In the design presented in this report, we chose an area with about half the precipitation required by the EPTM (assumed at 48" per year). This assures the necessity for irrigation of the EPTM, which will limit the topography of the site to some extent. However, it extends the range of the EPTM and is thus a critical aspect of the PEF concept.

Although 24 inches is specified as the average yearly rainfall, it is likely that annual variations in such rainfall will be at least ± 10 inches at times requiring additional irrigation water for the EPTM. Indeed, the site

TABLE 1
LIST OF IDENTIFIABLE PARAMETERS FOR
ALGAL POND SITE SELECTION IN A PEF

1. Availability and cost of level land (<1% slope or adaptable to 50-100 ft wide terraces).
2. Soil structure compactable for low percolation or available sealing clays.
3. Availability of non-toxic wastewaters (with specified nutrient content, seasonal distribution and distance from site).
4. High solar insulations (without extended rainy season or freezing conditions). Latitudes below 40°N.
5. Need of Energy Plantation for water and fertilizer.
6. Distance to Energy Plantations and markets for SNG fuel.
7. Distance of power plant or carbon dioxide source.
8. Labor availability (and social impacts).
9. Site-specific cost factors (construction, operational, transportation, waste credits, etc.
10. Suitable treated water storage locations (deep storage is most economical).
11. Environmental impacts (local and regional).

TABLE 2
SITE ASSUMPTIONS FOR ALGAL PONDS

PARAMETER	ASSUMED VALUE
Latitude	32°N
People	50,000
Sewage Transportation Distance*	5 miles
Daily total flows	5 MGD
Daily domestic flows	4 MGD
Daily industrial flows	1 MGD
Distance from CO ₂ source	10 miles
Yearly net evaporation	32"
Yearly gross rainfall	24"
Land costs (flat)	\$500/acre
Soil type	unspecified
Percolation	minimal
Water Costs (new source)	\$20/acre-foot

*This is an unfavorable assumption based on unfavorable cases for land availability. Sewage transportation distances could be much reduced in most designs.

selection of the PEF depends on variations in rainfall; one to two years of drought might have serious, long-lasting economic effects for the EPTM.

By growing algae to the N growth potential of the wastes, it should be possible to always grow a higher algal concentration (standing biomass) than required for complete light absorption at the depth of 30 cm (1 ft). Therefore, unlike oxidation ponds, it is possible to set a fixed depth and thus calculate a given detention time from a known (or assumed) visible sunlight conversion efficiency. This is not a generally agreed upon number; it changes (inversely) with light intensity. A design average of about 2.5% is utilized which is substantially less than could probably be achieved if species control for harvesting by microstrainers were not a consideration. Indeed, it is a critical assumption that by lowering achievable efficiencies by about a third, the slower growing, larger algae will be obtained which can be harvested by microstrainers. Additional factors must be considered, including inoculation, biomass recycle, and mixing, in selection of algal species. However, these do not directly affect the design of the system and are thus of only secondary concern at this time.

Each of the design assumptions listed in Table 3 is based on the considerations of optimizing overall efficiency of the process. N-availability for algal growth is of key importance since it determines the algal biomass produced and the fertilizer recovered for the EPTM. There is, however, the expectation that a temperature coefficient of bacterial waste destruction would lower the N availability somewhat in the winter. This is acceptable since the design calls for minimizing the pond size in winter. Algal harvesting efficiency, also assumed at an average of 80%, is likewise expected to be somewhat reduced in winter since operations would sacrifice species control for photosynthetic efficiency and thereby decrease area requirement. Solar conversion efficiency is assumed to increase in winter because of decreased incident light (see page 44) and the desired minimization of area requirements for winter. The value of α (of the Beer-Lambert equation) is a known variable, but at

TABLE 3

ALGAL POND DESIGN AND OPERATIONS ASSUMPTIONS

PARAMETER	AVERAGE VALUE	RANGE
N Availability	80%	75-85%
Algal Harvesting Efficiency (microstrainers)	80%	75-85%
Solar Conversion Eff. (PAR) (visible light)	2.7%	2.2%
α	$0.0015 \frac{\text{liter}}{\text{mg cm}^2}$	--
Operating Algal Concentrations	50% above optimal	40-60%
Depth	30 cm	--
C-availability	50% BOD ₅	--
N-content of Algae	8%	--
C-content of Algae	40%	--
Compensation Point	0.5 Langley/day	--

present not sufficient experience exists to assign a variable value to this parameter. The specifications of a higher-than-optimal algal concentration is again based on experience with recent experiments demonstrating the necessity of high algal concentrations for optimal algal harvesting (both through species control and because of a higher microstrainer efficiency at higher algal concentrations). The depth specified at 30 cm is a design choice dictated by construction costs. The shallower the ponds, the greater the care in leveling required. Shallow depth, however, maximizes algal concentrations and minimizes mixing costs. Opposing factors are the heating of shallow ponds (increasing evaporation) and faster diurnal changes. By keeping the depth at 30 cm, algal concentrations and detention times can be used to specify operations. This is, of course, only possible if maximal algal concentrations that can be grown on the available N exceed the desired or specified operating concentrations. This is always true in the design presented and should hold true in most cases (when not, biomass recycle is possible). C availability is (somewhat arbitrarily) set at 50% and is a minor factor which sets the carbon dioxide requirement. The N and C content of algae is set at 8% and 40%, although N can vary quite considerably. Finally, the compensation point (the light intensity at which photosynthetic oxygen production equals respiratory rates) was chosen at 0.1% of high noon incident light.

In Table 4 are listed the maximum and minimum probable average values of insolation--direct and diffuse--on a horizontal surface at sea level, in Langleys per day for both visible and total sunlight. A probable distribution of actual incident lights is assumed in Table 5 for a site at 32°N, assuming that its precipitation (and normal overcast) is restricted most to winter months). The range is between 100 to 280 Langleys per day for PAR. Ambient noon temperatures are assumed, based on experience and are not critical to the design. Ambient day temperatures below 10°C for prolonged periods or freezing would not be acceptable for a site location. The precipitation values chosen

TABLE 4

SOLAR RADIATION^a

Probable Average Values of Insolation—Direct and Diffuse—on a
Horizontal Surface at Sea Level, in Langley^b per Day

NORTH LATITUDE		MONTH											
Degree	Range	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	vis ^c tot ^d	vis tot	vis tot	vis tot	vis tot	vis tot	vis tot	vis tot	vis tot	vis tot	vis tot	vis tot	vis tot
0	max ^e	255 633	265 700	271 708	256 690	249 645	236 626	223 630	252 660	263 694	256 693	253 667	253 667
	min ^f	210 580	219 593	226 595	199 452	162 430	103 274	137 358	167 422	207 533	223 530	202 543	195 527
2	max	250 670	263 693	271 705	267 697	253 655	241 642	244 646	255 673	259 693	262 698	251 666	249 646
	min	205 560	213 560	224 594	193 454	164 404	108 288	141 375	169 442	206 531	220 521	198 526	189 505
4	max	244 650	259 698	270 704	258 701	258 653	247 635	250 657	258 678	269 695	250 680	246 650	244 628
	min	200 540	226 543	232 532	187 466	167 492	113 300	146 385	171 448	204 529	236 513	194 510	183 480
6	max	238 630	254 675	263 705	270 705	252 673	252 658	255 669	261 683	265 687	256 670	246 624	239 610
	min	192 520	199 530	209 530	195 467	189 500	118 310	150 355	172 452	202 524	191 500	188 494	176 460
8	max	230 610	249 665	267 700	270 709	265 635	259 678	260 630	263 688	267 695	252 660	234 616	231 590
	min	187 495	192 510	196 523	185 467	191 506	124 320	154 405	174 456	202 518	185 486	182 478	169 440
10	max	223 593	244 655	264 694	271 711	270 694	262 693	265 690	266 693	265 693	248 650	228 600	225 570
	min	179 475	184 490	193 513	173 451	192 512	129 330	158 414	176 460	196 510	181 474	175 462	162 420
12	max	216 572	239 645	262 690	271 710	273 707	267 700	269 700	257 697	264 691	244 640	221 585	217 550
	min	172 455	176 470	189 500	181 452	193 516	133 313	161 421	176 464	193 502	176 462	173 446	154 403
14	max	203 555	233 630	253 690	271 709	276 710	272 710	273 709	269 700	252 688	236 627	214 567	209 536
	min	163 430	167 450	184 467	179 460	194 524	137 354	164 429	177 467	189 496	170 449	162 430	146 380
16	max	200 530	226 610	255 670	272 707	279 718	276 720	277 715	270 703	253 684	234 615	206 554	200 520
	min	154 400	159 430	182 473	177 455	194 532	141 363	167 425	177 469	185 489	164 434	154 410	138 360
18	max	192 515	220 590	250 664	272 705	282 723	280 723	280 723	272 705	256 680	229 605	192 529	192 500
	min	144 360	150 410	174 459	174 452	194 530	145 375	176 442	177 471	180 479	157 418	148 390	129 340
20	max	183 500	213 575	246 652	271 703	284 730	284 733	282 723	272 706	252 674	224 598	190 520	182 480
	min	124 360	140 390	163 440	170 417	194 517	149 393	172 450	177 472	176 467	150 400	138 370	120 320
22	max	174 480	206 560	241 644	270 701	286 734	286 747	285 736	273 707	248 668	218 522	182 450	172 410
	min	124 335	132 370	162 425	167 440	193 530	152 392	173 454	176 472	170 455	143 380	128 350	110 300
24	max	160 460	200 545	236 625	268 657	283 738	283 753	287 742	273 708	244 659	212 568	175 480	161 410
	min	111 310	123 340	156 410	164 423	191 525	155 403	175 459	174 471	162 443	135 350	119 325	101 250
26	max	155 440	192 530	230 615	266 650	288 741	282 760	285 749	273 706	249 652	205 552	166 460	149 420
	min	99 250	114 310	149 350	160 425	189 513	158 409	177 463	172 463	160 429	123 332	109 300	90 250
28	max	146 420	184 510	224 603	264 653	289 743	284 764	288 755	272 704	236 625	199 537	157 440	138 400
	min	87 250	105 290	142 373	155 415	187 506	161 418	178 467	169 465	154 415	120 310	99 278	80 230
30	max	135 400	176 450	216 567	261 575	290 744	286 758	289 759	271 702	231 625	182 524	148 420	125 350
	min	70 220	95 260	134 332	151 405	184 500	163 425	179 466	166 452	147 399	113 250	90 250	70 210
32	max	120 380	169 470	212 570	258 653	290 741	286 772	289 761	269 700	225 615	185 510	134 400	114 350
	min	60 160	87 240	126 340	146 385	181 474	160 431	173 472	163 452	140 385	104 270	80 224	60 180
34	max	114 360	160 450	204 553	254 587	290 743	297 775	289 763	267 696	221 602	178 490	128 380	101 330
	min	53 155	78 215	118 320	141 385	176 452	168 430	178 472	159 448	124 368	96 250	70 202	47 150
36	max	104 335	150 430	195 535	250 630	288 741	299 776	289 765	264 690	215 590	170 470	118 360	86 314
	min	44 123	70 200	111 300	136 373	172 443	170 443	177 470	155 438	127 350	82 230	50 160	39 134
38	max	90 310	140 415	189 520	245 610	287 749	298 778	288 768	262 684	215 575	162 450	106 336	77 290
	min	30 120	62 180	103 280	131 355	166 420	171 418	175 464	152 429	120 330	80 216	50 158	30 111
40	max	80 300	130 390	181 500	241 570	286 732	298 776	288 765	260 680	203 562	150 430	93 313	60 270
	min	20 105	53 160	95 270	123 355	162 415	173 450	172 450	157 416	112 310	72 202	42 134	24 94
42	max	68 255	119 370	172 405	216 613	233 724	298 777	287 761	254 670	196 547	144 410	84 289	56 244
	min	20 90	45 140	88 250	120 344	157 405	174 451	167 442	143 403	105 290	65 187	34 112	19 76
44	max	55 228	105 340	155 470	230 607	280 722	298 777	285 755	250 660	185 530	132 390	72 263	47 218
	min	20 80	37 130	80 210	114 325	154 325	175 453	164 430	139 329	92 270	55 173	26 98	15 62
46	max	43 200	94 315	136 450	224 599	278 715	296 775	284 749	245 650	181 512	122 370	61 233	39 154
	min	16 74	30 110	72 210	108 315	150 365	175 455	161 420	134 374	90 250	52 158	23 86	11 48
48	max	35 180	82 290	143 430	218 532	274 710	297 776	282 740	241 640	174 496	111 350	50 210	32 170
	min	12 64	25 99	64 190	102 307	140 373	176 458	159 410	129 358	81 230	45 144	16 70	9 37
50	max	28 164	70 265	111 410	210 565	271 705	297 775	280 733	236 625	166 480	104 329	40 183	26 144
	min	10 54	19 80	53 173	97 300	144 371	176 450	155 403	125 342	73 210	40 130	15 60	7 30
52	max	22 140	60 240	134 392	202 555	257 695	296 776	278 725	232 615	158 450	87 307	32 160	21 121
	min	8 45	14 62	51 158	92 295	141 366	175 450	153 398	120 326	65 190	34 120	12 53	4 27
54	max	16 120	50 215	126 370	194 542	283 697	296 775	276 720	227 602	150 440	76 255	25 140	16 35
	min	6 40	11 45	46 145	88 289	139 360	176 460	150 391	116 312	58 170	29 106	9 43	3 23
56	max	12 102	43 200	120 350	193 523	258 680	295 775	273 714	218 537	141 420	64 261	26 120	12 78
	min	4 35	8 35	41 132	85 283	136 352	175 460	148 390	110 297	51 150	24 95	7 36	2 18
58	max	9 60	37 170	113 330	132 516	254 670	294 774	270 710	212 575	134 402			
	min	3 28	6 23	37 118	82 277	134 345	175 450	146 385	106 255	44 132	Algae Research Project Sanitary Engineering Research Laboratory Department of Engineering University of California, Berkeley		
60	max	7 64	32 150	107 310	176 500	249 650	294 773	258 702	205 556	126 386			
	min	2 20	4 20	33 105	79 270	132 340	174 450	144 330	100 270	36 116			

^a Calculated from data published by the United States Weather Bureau.

^b Gram calories per square centimeter.

^c "Visible" = radiation of wave lengths of 4000Å to 7000Å penetrating a smooth water surface.

^d "Total" = radiation of all wave lengths in the solar spectrum.

^e Value which will not normally be exceeded.

^f Value based on, or extrapolated from, lowest values observed for indicated month and latitude during 10 years of record.

Approximate corrections for elevation up to 10,000 ft.:

1. Total radiation: $\text{tot} (1 + 0.0185 \text{ El.})$

2. Visible radiation: $\text{vis} (1 + 0.00925 \text{ El.})$

Where El. is in thousands of feet.

Correction for cloudiness (approximate):

$\text{Min} + \{(\text{max} - \text{min}) \text{ cl.}\}$

Where cl. is fraction of time weather is clear.

TABLE 5: MONTHLY ENVIRONMENTAL CONDITIONS FOR SITE

Parameter (units)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Insolation, vis. (langleys/day)	100	120	170	200	260	280	280	250	200	140	110	100	Ave 180
Pond temperature (noon ave. °C)	10	12	14	16	20	24	24	22	20	15	13	11	Ave 17
Precipitation average (inches)	3	3	3	2	0	0	0	0	2	3	4	4	Σ 24
Evaporation gross (in class A pan) inches	2	2	3	5	7	9	9	7	5	3	2	2	Σ 56
Evaporation net (inches/month)	-1	-1	0	3	7	9	9	7	3	0	-2	-2	Σ 32
Evaporation net/pond cell (MG mo.)	-.81	-.81	0	2.4	5.7	7.3	7.3	5.7	2.4	0	-1.6	-1.6	Σ 26

are typical for regions requiring irrigation for farming and which would not be able to support an Energy Elantation without it. The final column in Table 5 presents net monthly evaporation per 30 acre high rate pond cell used in this design, the cumulative value amounting to 26 million gallons per cell per year.

The design of the Algal Pond System assumes a sewerred population of 50,000 people. The average present and projected loadings are listed in Table 6. Projected loadings indicate an increase in capacity of 25%. This should only affect the design of the pumping stations and primary treatment, with expansions of the ponds feasible by having additional space available. The composition of an average municipal non-industrial sewage is detailed in Table 7. Although this data shows sewage compositions higher than normal in total N content, it was chosen since it represents a desirable factor in the operation of an Algal Pond System for providing fertilizer to the Energy Plantation.TM In Table 8, existing loadings and their compositions are detailed. The industrial load, of about twice the BOD₅ and SS concentration as the domestic sewage, but lower total N and P, is seasonally distributed with peak loadings occuring during the summer months (see Table 9). Of course, a considerable amount of flow and load variations may be expected from the average values, but these would be mostly evened out by the long detention time of the ponds so that such short-term variation need not be included in design calculations.

The specific design components of the Algal Pond System are:

- (1) Sewerage connections and primary treatment; (2) High-rate algal pond;
- (3) Mixing and carbonation; (4) Algal harvesting; (5) Algae digestion.

These are detailed in the following chapters. In Figure 3 is shown a system design for large-scale algal production.

TABLE 6
PRESENT AND PROJECTED LOADINGS

	Present	Expected Capacity (in 10 yrs)
Connected Population	50,000	62,500
Average Annual Liquid Waste Flow*	4.0 MGD	5.0 MGD
Average Per Capita Flows*	80 gal	80 gal
Average Industrial Flow**	1 MGD	1.25 MGD
Total Per Capita Flows	100 gal	100 gal
BOD ₅ Loading Total, lbs/day ave.	11,400	14,250
SS Loadings Total, lbs/day ave.	10,500	12,625
Average Annual Flows	4.8	6.0
Minimum Dry Weather Flows, monthly average	4.5	5.6
Maximum Dry Weather Flow "	5.0	6.25
Maximum Wet Weather Flow "	5.0	6.25
Maximum Infiltration/Inflows	0.5	0.6
Average Dry Weather Flows	4.75	5.9

*Residential and commercial

**Seasonal maximum in summer months

TABLE 7. MUNICIPAL WASTEWATER CHARACTERISTICS FOR RAW SEWAGE (26-27)

Total Solids	1300 mg/l
Suspended Solids	250 "
BOD ₅	300 "
Total Organic Carbon (TOC)	300 "
COD	950 "
Total Nitrogen (as N)	65 "
Organic	25 "
Ammonia	40 "
Nitrites	0.1 "
Nitrates	0.1 "
Total Phosphorus (as P)	15 mg/l
Organic	4 "
Inorganic	11 "
Total Hardness (as CaCO ₃)	135 "
Total Alkalinity (as CaCO ₃)	130 "
Calcium	30 "
Magnesium	15 "
Iron	5 "
Aluminum	1 "
Sodium	200 "
Potassium	30 "
Silica (as SiO ₂)	15 "
Sulfate (as SO ₄)	120 "
Sulfides	30 µg/l
Chloride	260 mg/l
Phenols	90 µg/l
Oil & Grease	55 mg/l
Recalcitrant Materials	40 mg/l
Nickel	<0.1 µg/l
Manganese	0.16"
Lead	<0.2 "
Cadmium	<0.02"
Zinc	0.2 "
Copper	0.1 "
Mercury	0.0012 µg/l

TABLE 8. EXISTING LIQUID WASTES COMPOSITION

Liquid Waste Flows	MGD	BOD ₅		SS		Total N		Total P	
		mg/l	lbs/day	mg/l	lbs/day	mg/l	lbs/day	mg/l	lbs/day
Domestic (+ commercial)	4	300	10,020	250	8,350	65	2,170	15	500
Industrial**	1	600	5,010	500	4,175	45	375	7.5	60
Total	5	360	15,030	300	12,525	61	2,545	13.5	560

*Based on averages of one week's composites taken four times over one year during dry weather.

**Assumed to be mostly agricultural related or food processing. No heavy industry assumed. The industrial loading is seasonal (see Table 1).

TABLE 9: MONTHLY EXISTING LOADINGS

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Municipal Inflow MGD	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Industrial Inflow MGD	0.25	0.25	0.25	0.25	0.25	0.5	1.	1.	1.	1.	1.	1.
Infiltration Inflow MGD	0.5	0.5	0.5	0.5	0	0	0	0	0.5	0.5	0.5	0.5
Total Inflow MGD	4.75	4.75	4.75	4.75	4.25	4.5	5.0	5.0	5.5	5.5	5.0	4.75
N-Load Municipal lbs/day	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170
N-Load Industrial lbs/day	95	95	95	95	95	190	375	375	375	375	190	95
N-Load Total lbs/day	2,265	2,265	2,265	2,265	2,265	2,360	2,545	2,545	2,545	2,545	2,360	2,265
N-influent concentrations mg/l	57.2	57.2	57.2	57.2	64	62.9	61.1	61.1	55.5	55.5	56.6	57.2
BOD ₅ Load Municipal lbs/day	10,020	10,020	10,020	10,020	10,020	10,020	10,020	10,020	10,020	10,020	10,020	10,020
BOD ₅ Load Industrial lbs/day	1,250	1,250	1,250	1,250	1,250	2,500	5,010	5,010	5,010	5,010	2,500	1,250
BOD ₅ Load Total lbs/day	11,270	11,270	11,270	11,270	11,270	12,420	15,030	15,030	15,030	15,030	12,420	11,270
BOD ₅ Influent Concentration mg/l	285	285	285	285	320	330	360	360	330	330	330	285

FIGURE 3. SYSTEM DESIGN FOR LARGE SCALE ALGAE PRODUCTION

IV. SEWERAGE CONNECTIONS AND PRIMARY TREATMENT

The system must be designed to handle maximum expected loadings, e.g. the full municipal and industrial loads during peak summer months. These are detailed in Table 10 which contains the design values for the influent and primary treatment components. Designs in this chapter are based on Refs. 26-28.

The first is the provision of a sewage conveyance from the presently located pump station to the algal ponds. For design purposes, this will be assumed to be five miles, necessitating a 54" inch diameter sewer pipe^{*} with two pump stations (one intermediate, one influent to the treatment system) each working against a 40 ft head using 400 HP rated pumps of 7,500 gpm capacity (total for 10 pumps). The sewer line and influent pump station are standard practice and need not be detailed further (Table 10). The first step after the influent pump involves the removal of coarse solids from the wastewater by bar racks. The bar racks are placed in channels preceding the grit chambers and metering flumes. Dimensions of typical mechanically cleaned bar racks are 0.25" width, 1" spacing, 2" depth, with an approach velocity of 2.5 fps and an allowable head loss of 6". Two channels are normally specified to allow cleaning and maintenance without shutdown. The rate of accumulation of screened material at the bars is about 3 ft³/MG (at 50 lbs solids/ft³). (These are normally disposed of on land as solid wastes) (Table 11).

GRIT CHAMBERS

The grit chambers, which follow the bar racks, are generally designed by the criteria shown in Table 12.

*Alternatives which would be considered on a local basis are pressure conduits and open trapezoidal channels selection will generally be determined by land forms, elevations, construction problems, and local material and construction costs.

TABLE 10
DESIGN LOADINGS FOR PRIMARY TREATMENT

Plant Loadings	Design Value*
Flow (MGD)	6.5
SS (lbs/day)	15,000
BOD ₅ (lbs/day)	20,000
BOD _{ult} (lbs/day)	32,000
COD "	60,000
Total N "	3,200
NH ₄ -N "	2,000
Total P "	700
PO ₄ -P "	500
TDS "	100,000
Alkalinity m/gl	130
pH	6-10

*Maximum seasonal loadings expected within ten years.

TABLE 11
INFLUENT PUMPING AND PRETREATMENT

Trunk sewer connection distance (mi)	5
Number of pumping stations	2
Number of influent pumps	10
Influent pumps capacity gpm	7500
Influent pumps horsepower (HP)	400*
Head requirement (Static and Friction)	40
No. of bar racks	4
Width of channels (in)	36
Velocity (ft/sec)	2.5
Incline (degrees)	30°

*Actual horsepower for 7500 gpm @40 ft. head = 94.
However, reserve capacity is essential for flow variance and to compensate for breakdowns, etc.

TABLE 12
GRIT REMOVAL AND FLOW MEASUREMENT

Grit removal chamber No.	2
Size	50' L x 6' W
lbs/day	750

$$Q/A_s \leq 30,000 \text{ gpd/ft}^2 \quad (1.4 \text{ cm/sec})$$

$$V_{app} \leq 1 \text{ fps} \quad (30 \text{ cm/sec})$$

A fixed-width control section with vertical sides and a well-rounded approach should be selected so that the head loss may be assumed equal to 10% of the velocity head. A parabolic grit chamber cross section is required for constant velocity (= 1 fps). For a parabola, the area $A = 2/3 HT$, where H is the height and T is the top width. In the final design, the parabolic section can be approximated by straight lines. For the design flow of 6.5 mgd, $Q = 10$ cfs. For a 6-ft wide channel and a velocity of 1 fps, the depth in the grit chamber is

$$Q = AV = 2/3 HTV$$

$$H = 3/2 \frac{Q}{TV} = 3/2 \frac{(10 \text{ cfs}/2)}{6 \text{ ft } 1 \text{ fps}} = 1.25 \text{ ft}$$

when two chambers are used.

The length of chamber should provide removal equivalent to a 65-mesh screen (or $V_s = 3.7$ fpm under normal maximum flow conditions). The length can be calculated as: $1.25 \text{ ft}/3.7 \text{ fpm} \times 60 \text{ fpm} = 20 \text{ ft}$.

Thus, two 50 ft chambers would be used for grit removal to allow for turbulence at the inlet and outlet.

$$Q/A_s = 13,300 \text{ gpd/ft}^2$$

Metering by Parshall Flume:

Metering of flow is an essential requirement of plant design. In order to regulate the flow in the preceding parabolic grit chamber, it is

necessary to establish a critical depth at the throat of the flume. This requires an invert drop of three inches. With a throat (crest) width of one foot, flows of 0.35 to 16.1 cfs can be measured. Once the flume has been calibrated by suitable calculation, only the entrance depth need be measured. This depth of flow can be translated directly into rate of flow in cfs by means of an integrating recorder type instrument. For permanent installations, fiber glass forms are available which can be cast in place. Some units have built-in flow sensors.

Primary treatment will be designed according to conventional practice with a settling tank (followed by an optional sludge thickening unit). (28) The units should be designed to achieve a 50% removal of suspended solids and 30% removal of BOD_5 , resulting in a 13% removal of total N and 15% removal of total P (Table 13). The reason that primary treatment is designed along conventional lines and not by using facultative ponds is the requirement for sludge digestion to produce recoverable methane gas. Furthermore, facultative ponds are well known to lose a large fraction of total influent N which is a major consideration.

The sedimentation basins are designed (Table 14) at a detention time of one hour with a loading (overflow) of 1,000 gpd/sq ft. If two tanks are used of 3,000 sq ft, then the design load is almost reached. A 30 by 100 ft and 6 ft deep tank or channel would be used. The length takes also into account the influent bars and effluent weirs. A typical weir loading of 30,000-40,000 gpd/ft should be used. A sludge thickener is not specified in this design because of the proposed sludge digestion in ponds (see below). Recent designs for settling tanks have used gunnited trenches instead of formed concrete basins. These are more economical but less controllable. Control of primary settling may be less important with algal ponds than with conventional treatment, allowing a reduction in the size (and cost) of the primary treatment system. Inasmuch as most communities that will be considered for the PEF are likely to have

TABLE 13
REMOVALS IN 1^o TREATMENT (%)

BOD ₅ removal	30
SS "	50
Total N "	13
Total P "	15
Hydraulic flow reduction	negligible

TABLE 14
PRIMARY SEDIMENTATION CHAMBERS

Number	2
Size (ft ³)	18,000
Detention Time	1 hour*
Sludge (ft ³ /day)	1,800
(ss lbs/day)	6,000

*Minimum detention time used
to permit maximum nutrient
transmission to ponds

conventional primary treatment with settling tanks designed for 2-4 hrs detention time, it seems likely that such existing systems should be considered for utilization before additional structures are recommended. This, however, is again a consideration in site selection and cannot be dealt with on a hypothetical basis.

V. HIGH-RATE POND DESIGNS

The concept of the high-rate pond involves a shallow, mixed pond of short detention time which maximizes algal productivity and harvesting economy by its high algal density. (See Refs. 5,12,14 and Fig. 4 for schematics.)

The available data on high-rate algal ponds includes experience with small and large-scale waste treatment systems for example, St. Helena (4) and Modesto, California, as well as experimental ponds at a number of locations including Richmond, California, Israel, Germany, etc.). As shown schematically in Figure 2, the basic type of design is a channelized flow system which can be mixed at a relatively slow hydraulic velocity. High-rate ponds are operated from 8 to 20 inches in depth, 10 to 16 inches being the most common range.

Construction of high-rate ponds involves earthwork levees about 4 feet high around the perimeter. The levees have sloping (3:1) sides and a 10-15 foot driveway on the top for maintenance purposes. The inside baffles may be made of precast materials, being about 3 feet high and kept in place by poles. Flow in the channel is induced by pumps, paddlewheels, or other suitable means. The channels are about 50 to 100 feet wide and can be contoured to fit the topography. Due to the shallow depth and mixing requirements, leveling of the land within a few inches is required prior to construction. This is a major siting limitation for large-scale systems. If a very porous soil is encountered, a layer of clay or bentonite is recommended to seal the ponds; however, for most systems, the algae will rapidly seal the ponds' bottom so that water losses due to percolation (or ground water contamination by pond waters) are avoided after a few months. If pumps are used for mixing, a sufficient apron of cement must be designed to avoid churning up the bottom of the pond. A layer of crushed rock could be effective and allow reduction of the concrete area. The high-rate pond system can be constructed more quickly

FIGURE 4. SCHEMATIC VIEW OF HIGH-RATE POND 30-ACRE CELL

than most other waste management systems. Lifetimes would be long; the earth-works could last almost forever with proper weed control and erosion prevention and maintenance. Levees and baffles would have an expected lifetime of 50 years or more and pumps, 20 years or more.

The major variables that can be controlled in pond design and operations are mixing and recirculation, depth and detention times, carbon dioxide enrichment, pH, nutrient inflows, and algal detention times. These operational parameters are essentially "free," except for small incremental costs of, for example, extra mixing, harvesting, and pumping costs.

In standard oxidation pond design practice, the ponds are sized for the worst month (e.g. winter). By calculating the necessary algal concentrations required to produce the oxygen necessary to achieve desired reductions in BOD_5 , both depth and detention time are specified by application of the Beer-Lambert Law and an assumed photosynthetic conversion efficiency

1)	$C_c = \frac{\ln I_i - \ln I_c}{\alpha d}$	C_c = algae concentration
		h = heat of combustion
		d = depth
		I_i = incident light
2)	$F = \frac{h C_c}{I_i A \theta}$	I_c = compensation point
		A = area
		θ = detention time

For purposes of this project, it is necessary to design for the algal concentration required to remove organic N. This concentration will be higher than allowable at the shallowest practicable depth (≈ 10 in). The requirement for high conversion efficiency and biomass production necessitates a different operational detention period throughout the year.

Depth will be maintained constant (12 in). Algal detention time will then be varied throughout the year to adjust to changes in light inputs and algal growth rates. The system will, thus, be overdesigned for summer months when a fraction of the individual cells of the pond system will not be

operated. This allows for future expansion of this system to a complete nutrient removal system when algal growth to the P growth potential and higher productivities have been demonstrated.

By practicing biomass recycle for species control, a higher-than-optimal algal concentration will be achieved in the ponds which is also a consequence of specifying longer-than-optimal detention times.

Algal concentrations in the ponds are expected to run between 100-300 mg/liter throughout the year. Analysis of available data has not advanced enough to allow specification of optimal algal concentration (e.g. turbidostatic operation of the system at a particular insolation value with pre-set depth and variable detention time and algal biomass recycle).

The major design innovations are the variable monthly operation of the system as well as pH control and carbon dioxide additions with flue gas. The key to the success of the system is operation of the algal pond in such a way that it maximizes harvestable algal biomass production. On the basis of experiments performed during 1976-77 with three m^2 ponds (17) and with four twelve m^2 ponds (18), it is believed that high mixing, long detention times, biomass recycle, and high densities have significant probability of being conducive to algal populations with a yearly average of 80% harvestability by microstrainers. This is the key assumption of the design.

The expected effluent from primary treatment of municipal sewage (Table 7) is shown in Table 15. The reduction of BOD_5 is 30%, SS 50%, and total N 13%. Reduction in hydraulic flow is negligible, and removal rates are expected to be constant over the range of existing flows (4.5-5.5 MGD). Therefore, the expected monthly loadings for the high-rate algal ponds can be calculated from the given flows and loading rates from Table 9 and are shown in Table 16. This

TABLE 15. PRIMARY EFFLUENT (~99.8% of Raw Sewage)

Total Solids	1035	mg/l
Suspended Solids	125	"
BOD ₅	210	"
Total Organic Carbon (TOC)	195	"
COD	400	"
Total Nitrogen (as N)	56	"
Organic	9	"
Ammonia	40	"
Nitrites	<0.1	"
Nitrates	<0.1	"
Total Phosphorus (as P)	13	"
Organic	3.5	"
Inorganic	9.5	"
Total Hardness (as CaCO ₃)	132	"
Total Alkalinity (as CaCO ₃)	130	"
Calcium	30	"
Magnesium	14	"
Iron	3.5	"
Aluminum	0.8	"
Sodium	200	"
Potassium	30	"
Silica (as SiO ₂)	5	"
Sulfate (as SO ₄)	120	"
Sulfides	7	µg/l
Chlorides	260	"
Phenols	75	"
Oil & Grease	35	"
Recalcitrant Materials	17	"
Nickel	<0.1	"
Manganese	<0.02	"
Lead	<0.2	"
Cadmium	<0.02	"
Zinc	0.18	"
Copper	0.1	"
Mercury	0.0009	"

TABLE 16. MONTHLY LOADS FOR HIGH-RATE PONDS

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
N - Loading lbs/day	1970	1970	1970	1970	1970	2050	2210	2210	2210	2210	2050	1970
N - Concentrations mg/l (influent)	49.8	49.8	49.8	49.8	55.7	54.7	53.2	53.2	48.3	48.3	49.2	49.8
N - Available %	75	75	80	80	85	85	85	85	80	75	75	75
N-Algal Growth Potential lbs/day	18500	18500	19700	19700	20900	21800	23500	23500	22100	20700	19200	18500
N-Algal Growth Potential mg/l (effluent)	429	431	498	569	915	934	921	854	556	452	408	411
BOD ₅ Loading lbs/day	11270	11270	11270	11270	11270	12420	15030	15030	15030	15030	12420	11270
BOD ₅ Concentration mg/l (influent)	285	285	285	285	320	330	360	360	330	330	300	285
C-Algal Growth Potential lbs/day	9900	9900	9900	9900	9900	10900	13200	13200	13200	13200	10900	9900
C-Algal Growth Potential mg/l (influent)	250	250	250	250	278	290	316	316	287	287	261	250
CO ₂ Required mg/l (influent)	320	320	365	365	460	430	365	366	288	244	294	320
CO ₂ Required lbs/day	12700	12700	14500	14500	16300	16200	15200	15300	13200	11200	12275	12700

table also lists the expected total N that can be converted into algal biomass (75-85%) and from this the algal biomass that can be produced (algal growth potential) in lbs/day and mg/l (influent) is calculated on the basis of 8% N in algae. A similar calculation is made for BOD₅ and the algae (40% C) that can be grown on the assimilable C present in sewage assumed as 50% of BOD₅ the year. The difference between the lbs/day of algae grown on the assimilable N and C allows calculation of the additional carbon dioxide required each day (Table 17).

The final assumption that is necessary to design the size of the high-rate pond is the solar conversion efficiency for each month. These are indicated in the first row of Table 17. From a heat of combustion of 5.5 Kcal/gm for algae and the insulations given in Table 5, the productivity in gm/m²/day may be calculated. Since the amount of algae that can be grown on a daily basis is given in Table 16 the total area required to grow these algae may also be calculated. It should be noted that by selecting the given assumptions, it is possible to design a pond system which exhibits only a two-thirds differential in size between winter and summer, although insulations are almost different by a factor of 3. From the assumed algal harvestabilities during the year (from 75 to 85%), the total algal biomass produced (as against grown) can be calculated (Table 17).

The key operational variables not yet specified are the algal concentrations and detention times. From the Beer-Lambert Law, the optimal concentration that is allowable for any particular insolation and depth (set at 30 cm) can be calculated from equation 1.

Operational experience indicates that higher than calculated algal concentrations are desirable for harvestability (and species control), suggesting a factor of about 50% above optimal (indicated as operational algal concentration). This will set the required algal detention time, e.g. the time required to

TABLE 17

HIGH-RATE PCND OPERATIONS AND HYDRAULIC FLOWS

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	OCT	NOV	DEC
Assumed Photosynthetic Efficiency (%)	3.2	3.0	2.75	2.5	2.25	2.25	2.25	2.25	2.50	2.5	3.0	3.2
Calculated Algal productivity (gm/m ² /day)	5.5	6.5	8.5	9.10	10.6	11.5	11.5	10.2	9.1	6.4	6.0	5.5
Total Pond Area Required (acres)	360	320	260	245	220	215	230	260	270	360	360	380
Assumed Harvestabilities (%)	75	75	75	80	80	85	85	85	85	80	75	75
Total Algae Harvested (lbs/day)	13875	13875	14775	15760	16720	18530	19975	19975	18785	16560	15360	13875
Optimal Algal Concentrations (mg/l)	118	122	130	133	139	140	140	138	133	125	120	118
Operational Algal Concentration (mg/l)	165	170	200	200	225	225	225	220	200	190	170	165
Calculated Algal Detention Time (day)	8.7	8.0	7.2	6.8	6.4	6.0	6.0	6.6	6.6	9.0	8.7	8.7
Calculated Number of Algal Crops	2.6	2.6	2.5	2.8	4.3	4.0	4.3	4.2	2.7	2.3	2.4	2.5
Number of Cells Operated	12	11	9	8	8	7	8	9	9	12	12	12
Total Evaporation MGD	-0.32	-0.30	0	0.65	1.51	1.94	1.94	1.70	0.73	0	0.65	0.65
Total Inflow MGD	4.75	4.75	4.75	4.75	4.25	4.5	5.0	5.0	5.5	5.5	5.0	4.75
Total Outflow MGD	5.17	5.15	4.75	4.15	2.74	2.56	3.06	3.3	4.77	5.5	5.65	5.4
Hydraulic Detention Time (days)	23	21	18	19	28	24	26	27	18	21	21	22

grow one crop of algae. After harvesting, the effluent would be used to grow another crop. Detention times and number of crops that can be harvested are also indicated in Table 17.

The hydraulic flows in the system are also calculated in Table 17.

From the area required for algal growth, the number of individual pond cells (30 acres each, see below) can be specified. The algal concentration in the ponds can then be calculated and the hydraulic detention time must equal the algal detention times multiplied by the number of crops. It must be remembered that this design for a high-rate pond system is only given as an example. The design assumption (Table 3) must be first demonstrated experimentally with a reasonable or known level of confidence, and some factors must be determined at the particular site. It is clear that a few changes in assumptions could very significantly change the design outcome. This could best be determined by a computer sensitivity analysis for these factors.

It is clear that the critical assumptions which determine algal yields (and therefore methane and fertilizer outputs) are the photosynthetic conversion efficiency, the algal harvestability and the availability of influent N. Data is not available on which to select a final value. The assumptions and their annual variability were chosen on the basis of what is presently considered technically feasible and economically tolerable.

Photosynthetic efficiency could be assumed at 4% on the basis of presently existing information from experimental systems. However, the use of such values for large-scale systems cannot yet be defended and, more importantly, we assume a conversion efficiency loss occasioned by the species control operations required for use of microstraining as the harvesting technology. This is based on our present experience. The variations in

photosynthesis efficiencies throughout the year (a critical design assumption) are reasonable theoretically but are not based on experimental data.

Increases or decreases in photosynthetic efficiencies during winter months from those assumed proportionally decrease or increase the area requirements of the ponds as well as net evaporation rates. As the ponds are not the major cost component of the design this is not critical. The actual parameter of greatest importance is the harvestability: an increase of harvestability to 90% (average during year) could allow dispensing with the final settling ponds and increase biomass quantity by about 11% without any increased costs. N availability is a factor that exhibits similar responses as photosynthetic efficiencies and, of course, affects fertilizer outputs. It must be emphasized here that the N content in sewage chosen (see Table 7) in this design is well above the U.S. average.

The basic unit of high-rate ponds is the channelized cell surrounded by an earth embankment (Figure 4). For the purposes of this project, a 30 acre (working surface) cell unit is specified as shown in Figure 4 and high-rate pond design specifications are listed in Table 18. The cell is 800 by 1600 feet in size with earthworks 4 feet high and dimensions indicated in Figure 5.

The high-rate ponds are designed to be operated at a depth of 10-24 inches with mixing capacity of one foot/sec at the normal depth of 12 inches. Baffles are 36" high and installed in such a way that there is no leakage between channels. Influent weirs described previously will be located next to the sump for the pumping station. The effluent will go directly into a harvesting structure which will be common to four adjoining cells. From these reclaimed water flows in a channel to the storage ponds, or, alternately, the microstrainer effluents are passed to a second pond or recycled for additional algal growth.

FIGURE 5. TYPICAL CROSS SECTION OF HIGH RATE POND LEVEE.

Mixing in the 30-acre pond cells should be designed for a maximum speed of 1 ft/sec and a minimum speed of 1/4 ft/sec. Thus, four pumps per pumping station would provide the appropriate range of mixing speeds (i.e. one pump on for minimum flow, four pumps on for maximum flow). With a total channel length of approximately 14,000 ft/pond cell, two pumping stations will be needed. The head loss can be computed by Manning's Equation:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

$$1 \text{ ft/sec} = \frac{1.486}{0.013} R^{2/3} \left(\frac{H_L}{7000} \right)^{1/2}$$

$$H_L = .536 \text{ ft ft between pumping stations}$$

The horsepower requirement can be computed as follows:

$$HP = \frac{Q \cdot W \cdot H_L}{E \cdot 550}$$

$$HP = \frac{25 \text{ cfs} \cdot 62.4 \text{ lb/ft}^3 \cdot .536 \text{ ft}}{.25 \cdot 550 \text{ lb-ft sec/HP}}$$

$$HP = 6.1$$

Therefore, four 6 HP pumps per pumping station with two pumping stations per 30-acre pond cell will be required. The pump speed should be approximately 1125 RPM with 1/4 pitch blades. Since 1125 RPM equals 18.75 RPS and 25 cfs of water must be displaced per pump, approximately 1.3 ft³ must be displaced per revolution. To calculate the required diameter of the pumps, the following equation can be used:

(pitch) · (circumference) · (area) = volume of water displaced

$$1/4 \cdot \pi D \cdot \frac{\pi D^2}{4} = 1.3 \text{ ft.}^3$$

D = 15.4 inches therefore use 16"

Thus, 16-inch propellers with 1/2 inch flared ends can be fitted in a 16-inch standard pipe. The flared ends have been used in practice to increase the efficiency of the pumps. A transition pipe will also be needed to allow the 16-inch pipe to feed into a 12" deep pond. The transition outlet should be approximately 8" high by 24" wide. It should be remembered in specifying pond equipment that algae are sensitive to copper so that no brass or monel can be allowed to be in contact with the pond water.

An important engineering aspect in the pond design is the provision of a sump for the pumps and a concrete apron at the outlet to prevent erosion of the pond. The sumps are specified to be 6 feet deep and the concrete aprons are to extend 50 feet into the channels at the outlets. They are followed by another 50 feet of crushed rock. Finally, for proper mixing, deflectors must be installed at all corners to prevent eddying and accumulation of solids. Alternative mixing methods are available, including jet aerators paddlewheels, and air lift pumps. The only large-scale experience, however, is with propeller pumps. Construction costs for real systems on nearly level land in California (where leveling requirements were not larger than the earth works) are shown in Figure 6. Costs are related primarily to system size and depth. The most recent data for pond costs is about 1971 since the rigorous requirements of the new Public Law 92-500, together with the environmental quality acts, has actually resulted in a slow down in construction of algae pond systems and in a rapid increase in their construction costs. Fully-itemized costs for the Modesto system are shown in Appendix I.

FIGURE 6. ESTIMATED COSTS FOR PONDS, USA 1977

TABLE 18
HIGH-RATE POND DESIGN

No. of Cells	12
Size of Cells	30 acres
Length of Cells	1600 ft
Width of Cells	800 ft
Channel Length (total)	14,000 ft
Channel Width	100 ft
Number of Pumps/cell	8
Total Horsepower/cell	48 HP
Mixing Channel Velocity	2"-12"/sec
Mixing Schedule	22 hrs slow 2 hrs fast (strategic)

The engineering aspects of algal pond construction do not present any major unknowns nor require any technical breakthroughs. The choice of particular components (e.g. mixing systems, baffle materials, carbonation equipment) cannot yet be specified unequivocally. This is because insufficient experience exists on which to base a cost-effectiveness optimization. These issues are, however, not critical to the design of the algal pond subsystem of the PEF since it involves an integrated sewage treatment-bioconversion system whose economics is not totally dependent on methane (or fertilizer) outputs. In the proposed design, all major components (except pond carbonation) are based on presently existing practice of sewage treatment, with the pond designs being fairly conventional.

The major innovation proposed, and on which the design rests, is a variable schedule of pond operations which takes into account waste flows and solar irradiance and which maximizes production of algae harvestable by microstrainers. Without this new "software," the concept would have to be abandoned as conventional algal harvesting (chemical flocculation) is too expensive (by a factor of about four) and the resulting product would not be directly suitable for purposes of bioconversion. The pond operations assumptions and calculations (e.g. algal concentration times, harvestability, detention times, etc.) are only representative examples of the general type of operations that must be followed. The key concepts presented were the development of harvestable algal cultures by long detention times and relatively high algal concentrations. (The assumption of a photosynthetic efficiency was required to rationally set the detention time. In practice, the detention time is set by experience and the productivity is thereby fixed).

Two other concepts of proper pond operations (maximizing harvestable biomass)

are fast mixing and biomass recycle. Both operations further tend to reduce photosynthetic efficiencies. Prolonged fast mixing would tend to increase turbidity in the pond and increase power consumption while biomass recycle would increase algal concentrations even more above optimal than already achieved by long hydraulic detention times. The high algal concentrations will require more maintenance energy and thus a smaller fraction of light energy will be used in biomass production. The overall effect of these operations is judged to decrease harvestable production to about half of microalgal production feasible in high-rate systems (about 4% visible solar energy conversion efficiency). Furthermore, because of assumed harvesting losses and the fact that not all ponds are operated year-round, (particularly in the summer), total potential biomass production is about one-third of what may be expected under optimal conditions, optimal conditions being fast detention times and low algal concentrations.

An optimization between harvestability and productivity has not yet been undertaken. It may be expected that progress will be made with further experience and that a significant improvement can be achieved in algal productivity in the future. This, however, may only be achieved after considerably longer experience than presently available. It must be emphasized that the present experience is restricted to a few sets of experiments with four 3-m² circular ponds and the operation of four 12-m² ponds during one year. A limited set of experiments is completed with more presently underway. The results are encouraging: reproducible effects have been observed with long detention time and recycle on algal harvestability and low suspended solids in effluents have been consistently observed in the microstrained effluents of the ponds operated according to the criteria formulated above. Some control of algal species also was achieved in these experiments. It is doubtful that the present design assumptions (Table 18) will hold up in

unmodified form through an experimental pilot pond test. However, it is expected that the design approach will provide a useful guide for future work and modifications.

In actual practice a weekly review of pond operations would be required (if not more often) to maintain the system in the best operating ranges. The practice of operating such a pond system will require regular sampling of the ponds and determination of various parameters (e.g. chlorophyll, etc.). The results would have to be integrated with analysis of the influent wastes, solar insulations, temperature, etc. and translated into specific pond operations. This analysis and pond operations management will require operation of greater sophistication (and higher costs) than usual in the normal 5 MGD sewage treatment plant. However, the integration of the algal ponds into a larger PEF would allow this increased level of pond management.

VI. CARBONATION OF PONDS

The technology of low-cost carbonation for large-scale systems has not yet been developed. A fundamental question exists of whether the carbon dioxide should be introduced as dispersed bubbles in the liquid phase or whether the liquid phase should be dispersed in the gas phase. For the second approach, a power-droplet vs. surface area-contact time relationship must be established which is not foreseeable from present data on surface aeration.

Unlike oxygen, carbon dioxide absorbs primarily on the basis of available surface area and contact time, stirring has little effect (Table 19). Thus, it would not greatly improve matters to combine carbon dioxide injection and mixing systems, except for engineering and operational ease. Since, for the purposes of the PEF, these will be important (rather than cost or power minimization), they can be used in the design.

The amount of carbon dioxide required by the algal ponds is fairly small since algae will be grown only to the nitrogen-growth potential. Recent data demonstrates that complete nitrogen removal is possible even without carbon dioxide injection in long detention time systems (18). Another important effect is that of pH. Figure 7 shows the theoretical relationship and a few experimental points we were able to find in the literature. Since algal ponds will be operated between pH 8-9.5, it is apparent that a greatly facilitated carbon dioxide absorption will occur. The alkalinity buffering capacity is a further factor facilitating carbon dioxide absorption and storage by the system.

Because of the shallow depth of the algal growth ponds, any carbon dioxide sparger system would be an inefficient method of delivering carbon dioxide unless a deep sump is provided. Even at high partial pressures of carbon dioxide, considerable outgassing would occur unless one went to the extreme of using impellers to provide a high degree of turbulence.

TABLE 19
EFFECT OF MIXING ON CARBON DIOXIDE AND OXYGEN
MASS TRANSFER (pH 7.8)*

	nanomoles $\text{cm}^{-2} \text{sec}^{-1} \text{atm}^{-1}$	
	oxygen	carbon dioxide
Still Water	0.01	7.8**
Mixed Water	0.15	9.2

*Data from Reference 29.

**Calculated, other data is experimental

FIGURE 7. EFFECT OF pH ON CARBON DIOXIDE ABSORPTION

The rate of absorption of CO_2 depends on its solubility, a quality that is affected by the temperature and ionic strength of the water used in the scrubbing process. The solubility of carbon dioxide is independent of the pH, but because of chemical reactions (i.e. HCO_3^- , CO_3^{--}) the actual amount of carbon dioxide going into solution will be much greater than predicted by its solubility. However, for algal pond operations, a constant pH is desirable and thus carbonation of pond waters should not occur at a faster rate than required to replenish the CO_2 photosynthetically utilized. In the present analysis, only the rate of carbon dioxide absorption and solution into pond waters containing almost no dissolved carbon dioxide is considered (a reasonable assumption for pH range of 8-10). The solubility of carbon dioxide in water at 17°C is 0.04 gm moles/liter atm. Using the equation for ionic strength corrections:

$$\log \frac{H}{H_0} = -hI$$

where I is the gram ionic strength and h is a number which depends on the cations (h_+), the anions (h_-) and the gas (h_G) being considered:

$$h = h_+ + h_- + h_G$$

(For pond water:)

$$\begin{aligned} h_+ &= 0.090 \text{ l/gm ion} && \text{mostly } \text{Na}^+ \text{ and } \text{Ca}^{++} \\ h_- &= 0.025 \text{ l/gm ion} && \text{HCO}_3^-, \text{CO}_3^{--}, \text{Cl}^- \text{ and } \text{OH}^- \\ h_G &= 0.012 \text{ l/gm ion} && \text{CO}_2 @ 17^\circ\text{C} \end{aligned}$$

The solubility can be calculated as:

$$\log \frac{H}{0.04} = -0.103 \frac{1}{\text{gm ion}} \quad 1 \frac{\text{gm ion}}{1}$$

$$H = 0.032 \text{ gm moles/l atm CO}_2$$

Note that the solubility is proportional to the partial pressure of carbon dioxide (approximately linear up to 5 atm). This calculation does not consider chemical reactions (shifts in bicarbonate buffer or change in pH). To estimate the rate of absorption per unit of interfacial partial pressure of carbon dioxide (quiescent phases, no velocity profiles for either liquid or gas), the following equation from Sherwood et al. (30) can be used:

$$r = H\sqrt{kD} \quad \begin{array}{l} \text{mass transfer, diffusion with} \\ \text{chemical reaction} \end{array}$$

where H is the solubility, D is the diffusivity, and k is a pseudo reaction rate constant (after Nijssing Hendriks, and Kramers) (31).

$$D = 1.30 \times 10^{-5} \text{ cm}^2/\text{sec} \quad @ 25^\circ\text{C} \quad I = 2.0 \frac{\text{gm}}{\text{l}} \text{ ion}$$

Correcting for Temperature (to 17°C)

$$\frac{D_1 \mu_1}{T_1} = \frac{D_2 \mu_2}{T_2}$$

$$\frac{(1.3 \times 10^{-5})(.4493)}{567.6} = \frac{D_2 (.5288)}{548.2}$$

$$D_2 = 1.08 \times 10^{-5} \text{ cm}^2/\text{sec}$$

$$k = k_{\text{OH}} \times \frac{K_w}{K_2}, \text{ sec}^{-1}$$

and

$$\log k_{\text{OH}} = 13.635 - \frac{2,895}{T}$$

$$k_{\text{OH}} = 4490 \frac{1}{\text{g ion sec}} \quad @ 17^\circ\text{C}$$

$$\log \frac{K_w}{K_2} = - \frac{1568.6}{T} - 0.4105 + 0.00673T$$

$$\frac{K_w}{K_2} = 0.000136 \frac{\text{gm ion}}{\text{l}} \quad @ 17^\circ\text{C}$$

$$k = (4490) (0.000136) = 0.61 \text{ sec}^{-1}$$

The rate of absorption can now be calculated at 17°C:

$$\begin{aligned} &= H \sqrt{kD} \\ &= 0.032 \times 10^{-3} \frac{\text{gm moles}}{\text{cm}^3} \sqrt{0.61 \text{ sec}^{-1} \cdot 1.08 \times 10^{-5} \frac{\text{cm}^2}{\text{sec}}} \\ &= 8.21 \times 10^{-8} \frac{\text{gm moles}}{\text{cm}^2 \text{ sec}} \text{ per interfacial partial pressure of CO}_2 \end{aligned}$$

This value appears accurate based on some literature values.

Temp °C	$\frac{[\text{CO}_3^{=}]}{[\text{HCO}_3^{-}]}$	Ionic Strength	$k \text{ sec}^{-1}$	r
25	1.18	2.40	1.0	$7.3 \times 10^{-8} \frac{\text{gm moles}}{\text{cm}^2 \text{ sec atm}}$
25	0.96	0.94	0.75	10.75×10^{-8}
20	2.00	2.10	1.06	8.5×10^{-8}
20	0.50	1.50	0.27	9.8×10^{-8}

The Benfield hot potassium carbonate process achieves higher rates of absorption because the pseudo reaction rate constant and the diffusivity are both increased. Thus, the rate of absorption increases despite the decrease in solubility.

Example calculations: @ 60°C and equal carbonate and bicarbonate ions at 0.5 gm ions/l

$$I = 1/2 [(2)^2(0.5) + (1)^2(0.5) + (1)^2(1.5)] = 2.0$$

$$H_o = 0.017 @ 60^\circ\text{C}$$

$$\log \frac{H}{H_o} = -hI$$

(For the Benfield process)

$$h_T = 0.091$$

$$h_- = 0.021$$

$$h_G = -0.016$$

$$\log \frac{H}{0.017} = -(0.096) 2$$

$$H = 0.011 \frac{\text{gm mole}}{1 \text{ atm CO}_2}$$

$$D_{60^\circ\text{C}} = 1.30 \times 10^{-5} \frac{(.8904)}{(.4493)} \frac{(333)}{(298)} = 2.88 \times 10^{-5} \text{ cm}^2/\text{sec}$$

$$\frac{K_w}{K_2} = 0.001318 \frac{\text{gm ion}}{1}$$

$$k_{OH} = 8.74 \times 10^4 \frac{1}{\text{g ion sec}}$$

$$k = (8174 \times 10^4) (0.001318) = 115.14 \text{ sec}^{-1}$$

The rate of absorption for this process is:

$$r = H \sqrt{kD}$$

$$= 0.011 \times 10^{-3} \sqrt{(115.14) (8.74 \times 10^{-4})} = 1.10 \times 10^{-6} \frac{\text{gm mole}}{\text{cm}^2 \text{ sec}}$$

Summary of calculated rates of absorption.

Temp °C	$\frac{[\text{CO}_3^{=}]}{[\text{HCO}_3^{-}]}$	Ionic Strength	k, sec ⁻¹	r
17	0.1-1.0 pond water	1.0 pond water	0.61	$8.21 \times 10^{-8} \frac{\text{gm moles}}{\text{cm}^2 \text{ sec atm}}$
60	1.0	2.0	115.14	$1.10 \times 10^{-6} \frac{\text{gm moles}}{\text{cm}^2 \text{ sec atm.}}$

By using the Benfield hot potassium carbonate method, the rate of absorption can be increased by slightly more than an order of magnitude. Although this analysis applies to quiescent phases, the same increase in the rate of absorption should hold for the velocity profiles which will be encountered in any of the proposed carbonation schemes--with the actual rates of absorption increasing with increasing velocity profiles.

From the preceding analysis, it becomes apparent that the pond water is not a good choice of scrubbing water (i.e. low rates of absorption).

From a biological point of view, any scheme which employs the pond water for scrubbing water must also make special considerations for maintenance, clean up of the biological growth, nuisance control, and odor control. Such constraints add to the above conclusion that pond water is not a good choice of scrubbing water. Nevertheless, carbonation must be achieved.

The Benfield process is not applicable for carbonating the algal ponds, but it does point out the necessary operational parameters needed to achieve efficient rates of absorption. Since the demand for carbon dioxide is highest in the afternoon hours when the temperature is also the highest in the ponds, this will help in carbonation of pond waters. Also, the ionic strength of the ponds (specifically the K⁺ and Na⁺) can be increased by appropriate operational pond techniques.

As an alternative to the use of "scrubber" systems in which water is the continuous phase, the use of a method of carbonation using a surface aerator enclosed in a plastic dome and provided with either a scrubbed flue gas or digester gas atmosphere is possible.

Comparing a simple carbon dioxide diffusion process to a diffusion plus chemical reaction process, the important reaction for the high pH pond is:

and not the hydration reaction:

The significant parameter then is the ratio of concentrations of hydroxide ions in the bulk to the aqueous carbon dioxide at the interface $\frac{[\text{OH}^-]_o}{[\text{CO}_2]_i}$

From the law of mass action

$$[\text{OH}^-]_o = \frac{K_w}{K_2} \frac{[\text{CO}_3^{=}]}{[\text{HCO}_3^-]}$$

From previous calculation

$$\frac{K_w}{K_2} = 0.000136 \frac{\text{gm ion}}{1} @ 17^\circ\text{C}$$

and assuming $\frac{[\text{CO}_3^{=}]}{[\text{HCO}_3^-]} = 0.1$ for the pond water

then

$$[\text{OH}^-]_o = 0.0000136 \frac{\text{gm ion}}{1}$$

For all ratios of $\frac{[\text{OH}^-]_o}{[\text{CO}_2]_i}$ less than 15, the reaction is infinitely fast and is diffusion controlled (i.e. diffusion controlled reaction conditions prevail.) Since very small ratios would apply to pond systems, the carbon dioxide-air-water system is liquid phase controlling. That means the rate-limiting step in the diffusion process is the diffusion through the outermost thin liquid film. This situation dictates that a continuous carbon dioxide phase and a dispersed liquid droplet phase be used to achieve the best rates of mass transfer. Thus, surface aerators which disperse liquid droplets in a carbon dioxide-rich atmosphere while providing convective transport for increased rates of mass transfer are preferable to spargers or other bubblers. A more detailed analysis of this method is required in the future.

As mentioned in the first paragraph of this section, a theoretical analysis of this approach is limited and experimental tests must be undertaken before an engineering design applicable to pond systems can be recommended.

For the requirements of the design of the algal pond subsystem of the PEF, the choice of any of the available methods appears feasible because the amount of carbon dioxide that needs to be added is not large (see Table 17), at most about 16,200 lbs of carbon dioxide are required per day for this 5 MGD system. Assuming a 25% efficiency of transfer and 10% carbon dioxide content in the carbonation gas (e.g. flue gas) from the ideal gas law, it may be calculated that about 6.7 million ft^3 of carbonation gas will be required per day for the pond system with a maximum delivery rate of about 2,000,000 ft^3 per hour to the pond system and about 200,000 ft^3 of gas per cell per hour. The power requirements to get this CO_2 dissolved should be minimal.

Until sophisticated specialized systems are developed, various methods of carbonation may be used in an experimental PEF. Sparging tubes could be placed in the sump next to the pumps which are operated at full speed during peak times of carbonation. (This is required for any system to keep the pH in the ponds uniform). However, even at maximum mixing speed, about two hours are required for the plug of pond water to travel between sumps. Therefore, additional carbonation units will be needed. An arrangement in which a conventional Venturi with side outlet is used to draw gas into a long pipe used to provide long contact time for the pond water and carbon dioxide could be used at each pumping station.

VII. ALGAL HARVESTING

Algal harvesting is the critical technical limitation in the use of microalgae in sewage treatment and biomass production. Presently developed and available methods of algal harvesting are either too expensive (centrifugation, chemical flocculation) or unreliable (autoflocculation, microstraining). Algal harvesting has been the subject of extensive work at this laboratory (6) and has been recently reviewed (16).

The use of microstrainers for algal harvesting is detailed in other reports (17, 18). For the purposes of this design, commercially available units (supplied by the Crane Co.) of a size 10' x 10' will be specified. At a flow of 250 gal/ft²/hr (5,750 gal/ft²/day at 23 hrs/day), these units, with about 220 ft² of available straining area, can harvest about 1.25 MGD. Each pond cell will be operated at a minimum of about 6 day's detention time, which means a load of about 1.6 MGD per cell. If, however, it is remembered that, at the short detention time, only two out of three cells will be in operation, one algal harvesting unit per cell should be sufficient as long as provisions are made for interconnections to allow any harvesting unit to harvest the effluents from adjoining cells. This will be required also for maintenance, etc. Therefore, the harvesting units should be located in the adjoining corners of the cells which will lower construction and operation costs. The harvesting system will be installed, therefore, at a 15 MGD capacity.

The concentration achieved by the microstrainers is specified at ten-fold. Therefore, a secondary concentration method must be used to bring the algal solids concentration up to that required for anaerobic digestion (2-3%). This secondary concentration method will consist of two deep settling ponds (covered) which will be operated alternately with a

TABLE 20
HARVESTING SYSTEM

Size of Individual Unit	10' x 10'
Available Straining Area	220 ft ²
Fabric Loading Rate	250 gal/ft ² /hr
Capacity of Unit	1.25 MGD
Number of Units	12
Total Capacity of System	15 MGD
Energy Required	2600 KW HR/day
Minimum Algae Detention Time	8 days/12 cells 6 days/8 cells
Settling Ponds, Number	2
Settling Ponds, Size	1/2 acre, 12 ft deep
Settling Ponds, Operations	Two-day cycle, fill, settle-draw off
Isolation Ponds	3 x 10 acres, 15 ft deep

two-day cycle (one day fill, one day settle and draw off). Their size will be one-half acre each, 12 feet deep. The assumption that this settling process will work is based on observations with concentrated algae. The total installed capacity for microstraining will be 12 microstrainer units. Table 20 gives specifications for this system.

The algal harvesting system must be provided with a backup system in case of failure of species control and to remove the 15%-25% non-harvestable algal biomass. This will be provided for by three "isolation" ponds which will be 15 feet deep and 10 acres each in size. Each of these ponds will store 50 MGD of water, sufficient to receive all pond effluents for at least ten days followed by an equally long isolation time during which the algae settle to the pond bottom. The use of three of these ponds allows for maintenance (sludge removal) and increased flows or decreased algal settling rates. The storage of 150 MG of water in these ponds represents a significant water storage potential for irrigation of the Energy Plantation. This water storage also provides a reservoir for dilution water as required in pond operations (e.g. for microstrainer backwash). However, the approximately 1500 MG of reclaimed water effluent from the ponds per year would require a larger storage reservoir for utilization during the summer months when it is needed by the E.P.TM It is expected that a total of about 2,000 acres of Energy Plantation can thus be provided with irrigation water from a 400-acre (total effective area) pond system. The water storage reservoir should be a design component of the Energy Plantation, but local conditions, such as the availability of deep ravines, would dictate the design applied.

VIII. ANAEROBIC DIGESTION OF ALGAL BIOMASS

Data from laboratory experiments of algal digestion is summarized in Table 21. The first set of experiments represent the work of Golueke et al. (32) working with 11-liter batch digesters. Mixing was done once daily, prior to sludge removal and feeding. At loadings of .09 lb VS (volatile solids) per ft³ of digester volume per day, gas production was 6.4 and 8.1 ft³ per lb VS introduced per day at 35°C and 50°C respectively, corresponding to a volatile solids destruction of about 45% versus 55%. The composition of the digester gas was quite consistent, averaging 62% CH₄, 2% other combustibles, 32% CO₂, and 4% N₂ plus others.

Varying the solids concentration of the feed permitted detention periods from 3.3 to 30 days to be studied as shown in series 1B. In series 1C, loading rates were doubled from .09 to 0.18 lb VS/ft³ day. The resultant change in gas production was minimal.

Experiments 2A-2E are from the work of Uziel et al. (33) with 1.5 liter well-mixed cultures at 37°C. He attributed the higher gas production to the vigorous mixing of the digesters. Based on a heating value for Scenedesmus of 11,137 BTU's/lb VS (determined by bomb calorimetry), Uziel estimated algae-to-methane energy recoveries from 65% at loadings of 0.05 lb VS/ft³ day to 50% at 0.4 lb VS/ft³ day. His work also established the fermentability of other harvestable genera, including Micractinium, Spirulina, and Oscillatoria. All experiments reported that algal digestion cultures were quite stable with respect to shock loadings and other environmental changes.

FACTORS IN DIGESTER OPERATIONS

Figure 8 illustrates the effect of feed concentration on the relationship between loading rate and retention time (34). For a digester with no recycle, the liquid and solids retention time are equal. The curves show that for a given

TABLE 21. SUMMARY OF ALGAL DIGESTION DATA

Experiment ¹	Temp °C	Loading lb VM/ft ³ /day	Det. Time days	Gas Prod. ft ³ (STP)/lb VM Introduced	% CH ₄ in gas
1A	35	.09	30	6.4	62-64% consistently
	50	.09	30	8.1	
1B	50	.09	22	7.9	"
	50	.09	11	8.1	"
	50	.09	7	5.4	"
	50	.09	3.3	4.2	"
1C	50	.09	22	8.4	"
	50	.18	22	8.0	"
2A	37	.05	10, 15, 20 days	8.5	71% consistently ³
2B	37	.10	"	8.02	"
2C	37	.20	"	8.2	"
2D	37	.25	"	7.4	"
2E	37	.40	"	6.6	"

¹Experiments 1A-1C from ref.(32). Primarily Chlorella and Scenedesmus
Experiments 2A-2E from ref.(33). Primarily Scenedesmus

²Detention time had no systematic effect on gas production, so the average of the 5, 10 and 15 day runs are given.

³Ref. (33) corrected for the vapor pressure of the gas displacement solution (saturated NaCl + 5% H₂SO₄).

FIGURE 8. CONCENTRATION OF FEED SOLIDS AFFECTS THE LOADING AND RETENTION TIME RELATIONSHIP AS SHOWN

retention time, the solids loading will be reduced as the solids concentration of the feed decreases. Conversely, for a given loading rate, retention times decrease with lower feed concentrations. The minimum retention time is ultimately limited by the growth rate of methane-producing bacteria.

Golueke et al. found that gas production from algae decreased steadily at retention times less than eleven days, although little increase was observed at retention periods in excess of 15 days (34). Uziel et al. supported the latter claim. Since a minimum retention time of 10 days is necessary for maximum gas production from algae under laboratory conditions, fifteen or more days should be specified for a large-scale system.

Having set a lower limit on retention times, a trade-off develops between the cost of the digestion reactor and the cost of solids concentration. Low solids concentrations require larger digester volumes, whereas high concentrations, while reducing the reactor volumes, are more costly to achieve. If all costs were accurately known, the optimal concentration could be determined. The upper limit on feed concentration is usually considered about 10%, based on difficulties encountered in pumping, mixing, etc.

Uziel et al. (33) indicate a gradual decrease in energy conversion (and VS destruction) at higher loading rates, a phenomenon often observed in digestion studies. Such an effect would weigh into the trade-off between reactor size and feed concentration. However, the scatter in Uziel's data is considerable, and Golueke et al. felt the difference in gas production between .09 and .18 lb VM/ft³ day was not significant (32).

The most economical methods for removal of algae from ponds are sedimentation and screening ("microstraining") and are currently under investigation (17,18). The concentration of algae leaving the microstrainers ("concentrate")

currently runs about 1000 mg/l VS (0.1%). Since the present experiments are not concerned with maximizing concentrate densities, an improvement, perhaps to 0.2%, is likely. It is anticipated that further microstraining and/or sedimentation of the concentrate will increase this concentration somewhere between five and fifteen-fold (1-3%). This degree of settling has been observed in vessels of concentrate left standing overnight. Concentration techniques such as centrifugation and chemical precipitation, which are clearly too expensive for the dilute algal suspensions found in ponds, may be economical once the higher concentrations are reached.

It is well established that the anaerobic "methane-forming" bacteria are quite sensitive to both temperature and changes in temperature (35, 36). Data of gas production at various temperatures is included in Table 21. Golueke feels that gas production will fall off steadily below 30°C, although no data on algae digestion below this point is available except in quantitative observations on ponds. In addition to providing an optimal environment for the methane formers, it appears that the higher temperatures are helpful in insuring thermal kill of the algae, as viable cells are resistant to bacterial degradation. From the limited data available on temperature effects in algal digestion, the 35-38°C range would appear to be most economical. Higher instantaneous temperatures may aid in rendering algae more digestible, but this has not been studied.

The advantages of mixing digestion reactors include:

- a) the elimination of thermal stratification;
- b) the maintenance of intimate contact between feed material/nutrients and the microbial population;
- c) the removal of metabolic by-products which may cause local

inhibition of bacterial activity;

- d) the increase in gas transfer rates which may be the rate-limiting factors in anaerobic digestion (37);
- e) the creation of mixed-liquor conditions in all parts of the reactor (36). The prime disadvantages of mixing is the energy required in operation and the capital and upkeep costs of mechanically complex mixing systems.

Uziel et al. attributed the relatively high gas productivities in his experiments to vigorous stirring of the digesters. In the earlier digestion experiments, mixing was done only once per day by shaking the digesters' contents. Golueke has pointed out that since algal sludge is quite colloidal, it does not readily form the "sludge layer" characteristic of unstirred municipal sludge digesters.

In a large-scale system, some degree of mixing should be provided although the vigorous stirring characteristic of small laboratory digesters will certainly be impractical. Once it is established, vigorous digestion itself may provide all of the mixing required.

Specific problems associated with algal digestion include the degradation of the algal material, the potential for ammonia inhibition, and the nature of the digested sludge. The distinct cell wall characteristics of different types of algae will require for their digestion specifically adapted populations of fermentative bacteria; this is an important reason for species control in algal ponds.

The high nitrogen content of algae can lead to excessive ammonia concentrations which may inhibit fermentation directly or through an increase in digester pH (38). The latter mechanism would explain observations (33) of oscillating digester pH at long retention times. It is generally accepted that proteinaceous material is slower to degrade than carbonaceous, thus the

oscillations were not observed at shorter retention periods.

A major problem in algal digestion concerns the volume and nature of the digested sludge. As mentioned previously, the sludge is highly colloidal and hence difficult to dewater. The odor of the sludge can be described as similar to that of fresh cow manure. The C:N ratio will be quite low since the digestion process conserves nitrogen while losing carbon to the gas. It is not known what the distribution of nitrogen is in the sludge and liquid fractions of the digester effluents. Digester effluents and algal sludge should be an excellent fertilizer. Alternatives to its use in the Energy Plantation include direct application to croplands, composting with nitrogen-poor crop residues, or recycling to the algal growth ponds.

Design of Anaerobic Digesters

The algae harvested from the algal ponds will vary between 16,000 to 20,000 lbs/day of volatile solids. This amount of solids (about 10^7 gm/day) could be digested in a conventional digestion system which would require a volume of about 5.0×10^6 liter ($200,000 \text{ ft}^3$) if a volatile solids loading of about 2 gm/liter/day is used (corresponding to a ten-day detention time for a 2% feed).

In addition to the digestion of the algal biomass, the 1^0 sludge needs also to be digested. It is proposed to mix it with the algal sludge and digest all together. Since the 1^0 sludge has only about one-fourth the total solids content of the algae, it should be possible to specify increased loadings of the digester by this factor and retain an overall digester volume of 5×10^6 liter. Thus, for this design, two $100,000\text{-ft}^3$ heated and mixed conventional digesters will be specified. This technology is well developed.

The total amount of methane produced from the algae and primary sludge can be estimated between 80 M BTU's/day, and 100 M BTU's/day.

This does not take into consideration the digester heating

requirements, nor operational energy inputs into pond operations.

The available data on anaerobic methane digestion does not allow design of a cost-effective digestion system if methane has to be produced as part of a bioconversion system. The only apparent economical approach is the use of anaerobic ponds adapted to methane production. These systems are visualized as being much larger systems, with lower loading, limited mixing, and lower gas production rates per unit volume than presently achieved in municipal sludge digester designs. Two-stage systems must be used to allow complete digestion as well as storage and sludge separation. The first stage should be solar heated and mixed by recirculation. Use of power plant waste heat is an alternative source of heat to be considered. Gas will be collected by either a floating or a submerged gas catcher. There is little present practice on which to base a design of an anaerobic pond digester and further research will be required to collect the necessary data. Their loading cannot be specified.

At present, the only data we are aware of is that quoted by Mr. Kays of Globe, Inc., which installed a $108,000 \text{ ft}^2$ cover on an anaerobic pond which produces $174,000 \text{ ft}^3$ of methane/day.

In Table 22 are specified the characteristics of normal primary raw sludge, digested sludge, and digester supernatant. Since corresponding values for digested algal sludge are not available, these will be used with, however, the expectation that both the total N, ammonia N, and phosphorus will be substantially higher in the algal-sludge mixture to be digested. A most important consideration is the disposal of the digested sludge (and digester supernatants) at the Energy Plantation.TM The problems involved are both technical (involving EP fertilization operations which is outside the scope of this report) and economical (see next section).

It is expected that sludge storage and dewatering ponds will be required. These can be provided at very low cost, and require little area. It

TABLE 22
CHARACTERISTICS OF SEWAGE SLUDGES (after 27)

	PRIMARY SLUDGE	DIGESTER SUPERNATANT (69% of 1° sludge)	DIGESTED SLUDGE (31% of raw sewage)
Total Solids	6.5%	0.65%	6.0%
Volatile Solids (% of TS)	72 %	50 %	40 %
Oil and Grease (% of TS)	20 %	15 %	10 %
Protein (% of TS)	25 %	2 %	17 %
Nitrogen (as N % of TS)	2.5%	0.1 %	2.7%
Phosphorus (as P, % of TS)	0.5%	0.03%	0.8%
Potash (K ₂ O, % of TS)	0.4%	0	1.0%
Cellulose (% of TS)	10 %	0	10.5%
Iron (% of TS)	2.5%	.01%	4.0%
Silica (as SiO ₂ , % of TS)	15 %	0	16 %
Alkalinity (mg/l as CaCO ₃)	750 mg/l	3,300 mg/l	3,750 mg/l
Organic Acids (mg/l as HAc)	1,150 mg/l	100 mg/l	400 mg/l
BOD ₅ (100 mg/kg wet)	180	24	52

is not yet known how much of the N in the digester effluents (which equals the N content in the algae and sludge feed) can be applied to the EP.TM Assuming, however, that almost all the N in the algae can be converted into fertilizer (and including the N in the 1° sludge), this amounts to somewhat below 4,000 acres of Energy Plantations that can be supplied at the rate of 170 lbs. of N per acre per year. Therefore, the size of the AP Subsystem that can supply most water and fertilizer needs of the Energy PlantationTM would need to be in the ratio of about 1 to 10 in area (assuming both to require equal relative space for access roads, buildings, etc.). Of course, several restrictions have been put on this design: the low recovery of N first in the algae (two-thirds) and then in the conversion step of digester effluent to fertilizer (another two-thirds reduction). It would be expected that some of the nitrogen lost would wind up in the irrigation water.

The potential for significant future upgrading of the algal pond subsystem (see page 90) suggests that a size ratio of Energy PlantationTM and Algal Pond System of up to 20 would be the preferable design option since such a ratio would be feasible if provisions are made for future expansion of the Algal Pond System and if a sufficient alternative water supply for irrigation exists. Therefore, the design of an Energy PlantationTM of 11,500 acres should include the requirement of a 10 MGD local waste flow available within an economically feasible distance from the Energy Plantation.TM A minimum requirement of 5 MGD seems appropriate for maintaining a viable PEF concept.

An optimization may be made between the N fertilizer and irrigation water requirement of the PEF, local fertilizer and water costs. Depending

on the critical cost factor (whether fertilizer or water) the AP system can be designed to maximize the desired output: water through minimization of pond acreage during summer months and fertilizer through maximizing algal growth and nutrient recovery.

IX. COST AND ENERGY ANALYSIS

A requirement specified for the algal pond subsystem of the PEF is that it show a net savings in money and energy over conventional waste treatment systems. Based on EPA cost data (39) and available cost data for oxidation ponds (Fig. 5 and Appendix 1), this requirement can be met, even if unfavorable assumptions are made for the uncertain components such as carbonation, sewage pumping distances, and algal yields.

Table 23 gives a breakdown of the costs for the algal pond subsystem of the PEF. A major cost is for the importation of sewage, using force mains, over the five-mile distance assumed between the PEF and the population center. The costs of bar racks, grit chamber metering and primary sedimentation are together less than the cost of sewage transport. This cost could be reduced by locating the algal ponds closer to the population center and using open channels, at a cost savings of 65%, to transfer the reclaimed water. (Whereas the transport of raw sewage via open channels is unacceptable for public health reasons, the open transport of secondarily treated sewage would presumably meet public health criteria if the conveyance channel were properly fenced.) The savings realized would need to be discounted by the increased costs of sludge transport; however, sludge transport costs are small relative to the costs of application where distances of five miles or less are concerned (see Figure 9).

The costs of the fertilizer value vs soil application will be dictated by the application technology. These costs are presently not known. Roughly, it is expected that about five to ten tons of sludge solids would be produced per day in the algal ponds. Although the costs of the sludge disposal are not yet calculated for the PEF, it is clear

TABLE 23
COST BREAKDOWN FOR ALGAL POND SUBSYSTEM

Item	Cost/Yr. 1977	
<u>Primary Treatment</u>		
Sewage Importation @ \$19/MG/mi	\$174,000	
Bar Racks--Grit Chamber Metering @ \$7.15/MG	13,000	
Primary Sedimentation @ \$37.50/MG	<u>68,500</u>	\$255,500
<u>Secondary Treatment</u>		
Oxidation Ponds Capital @ 6%--20 yrs discounting	\$175,000	
Operations and Maintenance	25,000	
Algal Harvesting @ \$50/MG Microstraining	274,000	
plus \$5/MG Preconcentration	<u>27,400</u>	\$501,400
<u>Digestion</u>		
@ 1¢/lb dry solids		
5 x 10 ⁶ lb algae/year	\$ 60,000	
2 x 10 ⁶ lb primary sludge/year	<u>20,000</u>	\$ 80,000
TOTAL		\$836,900

Sewage importation costs include costs of force mains, pumping and maintenance but not excavation, according to the relationship given in Figure 7 of Benemann *et al.* (39). Costs for bar racks, grit chamber metering, and primary sedimentation were taken from the EPA manual, Cost-Effective Wastewater Treatment Systems (39).

Construction costs for the high-rate ponds at Modesto, California (see Appendix I) were about \$2,500 per acre for a 860-acre system; due to the smaller system size and subsequent inflation in general construction costs this figure was doubled in estimating the cost of the 360 acres of high-rate ponds for the Algal Pond Subsystem. The 30 acres of isolation ponds were also estimated to cost \$5,000 per acre, because the added excavation is offset by their absence of mixing stations. Total construction cost of the algal ponds was pegged at \$195,000, amounting to \$175,000 yearly.

Algal harvesting costs were detailed in (17) and, for the microstraining component, are approximately \$50/MG. However, three crops of algae, on the average, are required to deplete the influent sewage of its N content and therefore the microstraining costs will be tripled. Before digestion is possible, the harvested algae must be further concentrated; this, when accomplished by gravity sedimentation, is estimated to add about 10% to the harvesting costs.

FIGURE 9. TRANSPORTATION AND DISPOSAL COSTS FOR SLUDGE UNDER VARIOUS CONDITIONS

that it should not be a significantly higher cost than that of conventional systems. Conventional systems have the same problem in disposing of sludge, which sometimes approaches in magnitude that derived from the algal ponds, particularly in advanced chemical treatment systems.

Therefore, it is expected that, in either case, conventional treatment costs will not be exceeded, even without considering the economic benefits of the fertilizer value of the algal sludge.

The high-rate ponds are of conventional design, expected to cost about the same as those presently existing. The largest of these pond systems is in Modesto, California, and the actual contractor's cost report is reproduced in Appendix I. Although of obviously a different design and not directly applicable, the approximate 1977 costs of the system designed above (which is slightly less than one-half the size of the Modesto System) are about \$5,000/acre (Table 23). The harvesting costs must be added onto this: they consist of a 15 MGD capacity micro-strainer system and operation of the secondary settling and final algal removal ponds. The latter are of negligible costs, the former are estimated at almost \$300,000/year capital and operating costs. (A major component in the cost estimates are the manpower costs.) Thus, the pond costs (\$200,000/year) are about 40% of total costs and result in a total approximate cost estimate of \$837,000/year (which does not include the management of the pond system, at present a major uncertainty). This cost is comparable to conventional systems of the size (5 MGD) practicing conventional secondary sewage treatment and meeting 1977 EPA standards. These cost estimates should be considered preliminary at this stage. They need refinement and further analysis.

The cost of digestion, when carried out in conventional, mixed, heated concrete reactors, was estimated at 1¢/lb dry solids using the EPA Manual (39).

Table 24 contains a summary of energy inputs and outputs of the algal pond system. About 500 acres of total algal pond system produce an equivalent of less than 0.5% of the average energy usage of 50,000 people, the sewered population. This is less than what can be expected for non-regenerative bioconversion system, particularly since, in this case, both net energy output and energy "conservation" (in fertilizer, water, and waste treatment) are considered. These relatively low net outputs are due to the very conservative nature of the design, reflecting present state-of-the-art rather than future potential.

The design and cost estimates are presented on the basis of what is believed to be present state-of-the-art. The basic assumptions about algal harvestability which influence greatly the design and costs are based on experiments not yet concluded and must still be tested in pilot pond studies. The design is conservative in algal productivity values; about a 50% improvement could be expected through operational experience. Many areas for cost reduction and technological advances can be specified, and the expectation is that costs can be decreased and outputs increased over those specified in this design. Thus the cost and energy outputs of this design are not final.

If the concepts of low-cost large-scale algal bioconversion systems described above are developed, a considerable upgrading of the system would be possible in the future. Since the system is designed to operate in the N growth limitation range, any increase in algal biomass production would require additional N inputs. These would be best supplied by use of nitrogen-

fixing blue-green algae which can grow up to the P growth potential of the sewage. If a 50% increase in solar efficiency is assumed with a 10% increase in harvestability and full-time operation of the pond systems, a doubling in both methane and fertilizer outputs could be achieved using the same facilities with only a modest additional evaporation of wastewater. Thus, it is clear that considerable potential for upgrading exists for the present design through development of proper pond operational procedures.

Specific improvements in design of facilities can also result in considerable cost reductions. For example, an alternative mixing station design incorporating paddlewheels may be used. Paddlewheels as wide as 20 feet or more are probably feasible. The design and layout of a 30-acre pond cell mixed by paddlewheels

TABLE 24
ENERGY INPUTS AND OUTPUTS TO ALGAL PONDS

Item	Inputs	
	KW-Hr./day	M BTUs/day
Sewage Conveyance	2000	20
1 ⁰ Treatment	750	7.6
Mixing & Carbonation of Ponds	540	5.5
Harvesting	2600	26
Digestion	<u>4300</u>	<u>44</u>
Total	10190	103
	Outputs	
	Quantity	Equivalent MBTU/day
Methane	about 20,000 lbs	100
Fertilizer	sludge/day	35
Water--Reclaimed	~4 MGD	50
Waste Water Treatment	5 MGD (2 ⁰)	<u>35</u>
Total		220

Net output ~120 M BTUs Energy equivalent/day.

would resemble that shown in Figure 4 except that four paddlewheel mixing stations would be used in lieu of the two pumping stations. At each station, five paddlewheels, each 19.5 feet wide, span the channel. The shaft supporting the paddlewheels is supported at 20-foot intervals, and is driven by two, 6 HP motors (one at either end of the shaft) through a two-speed transmission system, incorporating a torque converter to enable smooth startups. The direction of mixing by the paddlewheels would be reversed daily in order to prevent sludge deposits from accumulating. Although large-scale experience with the use of paddlewheels for mixing is not available (as it is for pumps); the application of brush aerators to algal pond mixing in Israel indicates that the same generally efficiency of mixing as obtained with pumps can be realized with paddlewheels. Use of paddlewheels would significantly reduce capital costs for pond systems as well as improve pond operations.

The costs of algae harvesting may be reduced if a preconcentration method, based on rapid settling or floatation by the algae, can be developed; this is the subject of a current study (41). The five miles of pumping distance specified in the design is very site specific and should probably not be charged against the algae pond operating costs. Anaerobic digestion could probably be reduced in cost with development of proper technology. The cost estimates (as well as energy inputs-outputs) require further refinement for a final design.

Thus, considerable improvements appear possible for the algae pond subsystem of the PEF. The cost estimates and engineering designs presented above are conservative and reflect the presently minimal assumptions which allow the algae pond system to meet the basic specified requirements of energy and cost advantages over conventional systems (e.g. chemical fertilizer for the EPTM and activated sludge for waste treatment).

X. INTEGRATION OF THE PEF

The engineering design and cost analysis for the algal pond subsystem of the PEF is, as pointed out before, based on the assumptions made regarding state of the art and location of the PEF. The design presented above was chosen to allow maximization of N fertilizer and water reclamation potential of the algal pond subsystem. Several key uncertainties remain, particularly regarding the applicability of the harvesting methods chosen.

The InterTechnology/Solar Corp. carried out a more detailed computerized design effort which it applied to fifteen potential sites. One basic design assumption was a 4% solar conversion efficiency in the worst month which is similar to the assumptions made here. However, this assumption will only hold in the more favorable locations and requires a decrease in algal concentration in the growth ponds. (Below a certain critical value of light intensity, algal yields drop to zero.) Using lower N concentrations in the waste flow, they calculated about 14 MBTU/day of methane (net output) and 240 lbs N fertilizer/day for a 1-MGD system which would use 48 acres of pond area and operate under N limitation. Most importantly, they calculated a net positive cash flow of \$152,000/yr for such an algal pond system (with over 90% of cash flow coming from waste treatment credits). Use of nitrogen-fixing algae would increase waste treatment credits 50% (for tertiary treatment) and methane outputs by about 3.4-fold while increasing pond area and capital investments 4-fold. This decreased cash flow amounts to \$58,000/yr, which was not considered cost effective. However, if the annual expense of the nitrogen-fixing algal system could be reduced by 25%, then the system could produce methane at a present equivalent cost of \$2/MBTU methane. This emphasizes the need to develop the state of the art of nitrogen-fixing algal cultivation technology.

Without waste treatment credit for N removal, the most cost-effective system was actually a C-limited pond system (net cash flow \$213,000) as the additional methane yields from the N-limited case did not justify the two-fold higher pond areas required.

The critical assumption of their design was harvesting with micro-strainers; use of conventional harvesting technology (dissolved air flotation) resulted in a negative cash flow of \$171,000 (e.g. conventional waste treatment with activated sludge would have been more cost effective). Another design consideration was the size of the system--below 1.0 MGD, severe diseconomies of scale were apparent.

The integration of the algal pond with an Energy Elantation involves three major flows: carbon dioxide from the power plant to the algal ponds, water, and fertilizer (digested algae and primary sludge) to the Energy Elantations. In addition, minor transfers of waste heat and ash from the power plant to the algal pond could be involved. The carbon dioxide transfer was assumed in this design to be 50% efficient while the InterTechnology/Solar Report indicated a 15% transfer efficiency. It may be assumed that in actual practice the transfer efficiency achieved may be between these values; certainly the lower value is more realistic since little practical experience exists. Therefore, the output of the power plant must be at least large enough to satisfy the carbon dioxide needs of the algal ponds several-fold. Furthermore, the carbon dioxide requirement is highest in the summer and in the afternoons; thus, the sizing of the power plant (and the carbon dioxide transfer system) must be based on the maximal rates of carbon dioxide consumption, not daily or monthly averages. Considering the higher biomass yields of algal ponds, the efficiency of carbon dioxide transfer, and the peak carbon dioxide demand rates, a properly sized power plant fueled by Energy Plantation fuel alone would require an Energy Plantation of about 50 times as large as the algal ponds.

It should also be noted that algal ponds would be capable of disposing power plant waste heat as temperature is not a critical factor in pond operation. Indeed, in the winter, this would be beneficial, while in summer, it would lead to higher rates of evaporation. Ash recycling back to the Energy PlantationTM rather than to the algal ponds is probably preferable.

The fertilizer requirements of the Energy PlantationTM are given as 165 lbs/acre/year. In our 5-MGD N-limited design, we expect an N recovery averaging 2,000 lbs N/day. This corresponds to a fertilization capability of about 4,000 acres of Energy Plantations. By comparison, the InterTechnology/Solar Corp. N-limited design (scaled to 5 MGD) produces only 1,200 lbs N/day. The discrepancy is based on the much higher N values for N content assumed in our design. Therefore, their fertilizer production rates may be considered more reasonable and the ratio of Algal Ponds to Energy PlantationTM which can be self-sufficient in fertilizer, is thus, at most, 1:10. This ratio is more or less independent of algal pond size, except for C-limited systems (e.g. conventional secondary treatment) where primary sludge N content allows a ratio of up to 1:16 of AP to EPTM. (Of course, C-limited systems are only one-half the size of N-limited or 1/8 the size of P-limited ponds. Providing fertilizer free of charge to the Energy PlantationTM could reduce the cost of the wood biomass significantly, amounting to about \$4/ton out of an average cost of \$20/ton (e.g. a 20% cost reduction). Of greater interest would be the application of the wastewater "credit" (calculated by ITC) in reducing the cost of the wood biomass. One acre of N-limited algal pond generates enough cash flow to subsidize wood biomass production on ten acres of EPTM sufficiently to make up for a doubling of costs occasioned by decreasing the scale of the EPTM to 5,000 acres.

The final question is how much water can the algal ponds provide to the Energy PlantationTM? Although the InterTechnology/Solar Report assumed no irrigation water, the application of irrigation water is considered in other silviculture systems analyses, and it is clear that two acre-feet/acre-year irrigation would greatly extend the range of the EPTM, fulfilling one of the objectives of the PEF. Assuming sufficient water storage and an average outflow of 4 MGD from the 5-MGD system proposed in this report, about 2,000 acres of EPTM could be supported by the 400 acres of algal pond system or a ratio of 5:1. Of course, water will be of poorer quality and available in smaller amounts if ponds are expanded to the P-limit of sewage. Thus, three ratios have been obtained for the desirable AP:EPTM ratios in the PEF: 1:50 for carbon dioxide production, 1:10 for cash flow and also for nitrogen fertilizer, and 1:5 for water reuse. The first ratio can be decreased by burning wastes or residues (or other solid fuels) in the power plant (Figure 1). The cash flow ratio is of doubtful validity: why would a cash waste treatment credit be applicable to an EPTM? There is some validity in using the EPTM to dispose of excess sludge (providing the fertilizer as a consequence) and wastewater effluents. Therefore, the acceptable ratio would be closer to 1:10. Obviously, some uncertainty is involved and considerable variability from location to location, suggesting a range of 1:5 to 1:20 for AP:EPTM. However, the average AP:EPTM ratio should be about 1:10. The diseconomies of scale for such a relatively small EPTM dictate a minimum size of about 5,000 acres, even when subsidized by the cash flow of the algal ponds. Such a system would, therefore, not be limited by water, fertilizer, or production costs. This assures early implementation. Research needs to be continued on the harvesting of microalgae which is, obviously, the critical assumption on which everything hinges. For the longer range, research on nitrogen-fixing blue-green algae is imperative.

XI. CONCLUSIONS AND FUTURE DEVELOPMENTS

This design effort must be characterized as only preliminary.

An effort was made to develop a detailed and realistic microalgae wastetreatment bioconversion system as far as present technology would allow. (See Table 25.)

It is clear that present oxidation pond microalgae harvesting technology was only marginally cost effective, requiring assumption of low-cost harvesting technology in this design. Many details of the system need further work: cost and energy analyses are only a first approximation, mixing and carbonation systems need more designs as do sewage conveyance and water-fertilizer disposal methods, etc. However, the key immediate need is the determination of the accuracy, applicability, and necessary modification of the operation design assumptions (see Table 3). Until these are substantiated by more detailed, larger pilot plant results, it will serve little useful purpose to optimize, computerize, or otherwise improve on the design. Thus, the major future effort should be the experimental verification of the design assumptions by operation of a pilot-scale algae pond.

The PEF concept will only become practical if fully integrated into the local energy-water-waste flows. The amount of biomass suitable for anaerobic digestion or combustion represented by agricultural residues and urban wastes could easily rival the outputs of the PEF. Figure 1 shows a schematic representation of the energy-water-wastes-biomass flows in a locality using the PEF concept. Only through a detailed quantitative analysis will it be possible to maximize the benefits of bioconversion for a specified locality.

TABLE 25
SUMMARY OF PRELIMINARY ALGAE POND DESIGN

A) <u>Main Assumptions</u>	
Design Size Average	5 MGD (50,000 people)
Critical Waste Characteristic	65 mg/l N
Critical Operations Assumptions	80% harvestability 2.5 Average% Solar Conversion (PAR)
Sewage Transportation Distance	5 miles
B) <u>Design Specifications</u>	
1 ^o Treatment (including sewage conveyance)	Conventional
Oxidation Ponds	12 cells of 30 acres each 100 ft wide channels 8 pumps of 6HP each 22 hours slow mixing/2hrs fast mixing
Algae Harvesting	6.7 x 10 ⁶ ft ³ of flue gas/day 12 x 1.25 MGD Microstrainer with 2 x 1/2 acre settling ponds 3 x 10 acre isolation ponds
Algae and Sludge Digestion	Conventional
C) <u>Costs (\$/Year)</u>	
1 ^o Treatment	\$255,500
Oxidation Ponds	\$200,000
Algae Harvesting	\$301,400
Methane Digestion	\$ 80,000
TOTAL	\$836,900
D) <u>Energy Balance</u> (MBTUs/day)	
Total Inputs	103
Outputs	
Methane	100
Fertilizer	35
Reclaimed water	50
Waste treatment	35

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APPENDIX I. ACTUAL COST DATA FOR 860 ACRE MODESTO, CA PONDS, June, 1970

ITEM NO.	DESCRIPTION OF ITEM	CONTRACT			COMPLETED TO DATE		COST OF UNCOMPLETED WORK	%
		QUANT.	COST PER UNIT	TOTAL COST	QUANT.	TOTAL COST		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	Clearing & Grubbing	LS		39,758		39,758.00	-0-	100
2	Land Leveling	LS		41,200		41,200.00	-0-	100
3	Borrow Pit Fill	37,000 CY	0.27	10,360	26,363	7,104.51	-0-	-
4	Embankment	770,000 CY	0.42	323,400	695,795	292,233.90	-0-	-
5	Shape Access & Site Rds.	120 Sta	21.00	2,520	120	2,520.00	-0-	-
6	Drain Ditch Excavation	91,000 CY	0.42	38,220	94,131	39,530.82	-0-	-
7	Fine Filter Aggregate	1,800 Ton	4.50	8,250				
8	Course Filter Aggregate	1,800 Ton	4.25	7,650	5658	25,035.65	-0-	-
9	Impervious Blanket	108,000 SY	0.16	17,280	17,650	2,824.00	-0-	-
10	Rip Rap 12" Depth	22,000 Ton	3.45	75,900	18,713.92	64,563.02	-0-	-
11	Rip Rap 6" Depth	5,000 Ton	3.70	18,500	3,741.78	13,844.59	-0-	-
12	Rip Rap Stockpiled	1,000 Ton	3.20	3,200	1,065.10	3,408.32	-0-	-
13	Aggregate Base	33,000 Ton	3.40	112,200	46,662.30	158,651.82	-0-	-
14	Asphalt Concrete	2,800 Ton	8.00	22,400	4,992.30	39,938.40	-0-	-
15	Type I Gate Structure	18 Ea.						
	a. Excavate & Backfill	10,410 CY	0.65	6,810		6,810.00		100
	b. Concrete	623 CY	130.00	80,962		80,962.00	-0-	100
	c. Mechanical			50,199		50,198.00	-0-	100
16	Type II Gate Structure	13 Ea.						
	a. Excavate & Backfill	8,830 CY	0.62	5,459		5,459.00	-0-	100
	b. Concrete	760 CY	102.00	77,508		77,508.00	-0-	100
	c. Mechanical			48,983		48,982.00	-0-	100
17	Type III Gate Structure	1 Ea.						
	a. Excavate & Backfill	862 CY	0.57	493		493.00	-0-	100
	b. Concrete	105 CY	92.00	9,664		9,664.00	-0-	100
	c. Mechanical			7,618		7,618.00	-0-	100
18	Type IV Gate Structure	3 Ea.						
	a. Excavate & Backfill	3,730 CY	0.53	1,965		1,965.00	-0-	100
	b. Concrete	593 CY	87.00	51,597		51,597.00	-0-	100
	c. Mechanical			45,063		45,063.00	-0-	100
19	Type V Gate Structure	1 Ea.						
	a. Excavate & Backfill	595 CY	0.65	385		385.00	-0-	100
	b. Concrete	38 CY	120.00	4,568		4,568.00	-0-	100
	c. Mechanical			3,247		3,247.00	-0-	100
20	Elec. Gate Hoist Operator	1 Ea.	700.00	700		700.00	-0-	100
21	Drainage Wells	16 Ea.	922.00	14,752	16	14,752.00	-0-	100
22	Observation Wells	25 Ea.	59.00	1,475	25	1,475.00	-0-	100
23	Water Well	LS		520		520.00	-0-	100
24	Chain Link Fence	2,130 LF	3.00	6,390	2,104	6,312.00	-0-	-
25	12' C/L Swing Gates	10 Ea.	160.00	1,600	10	1,600.00	-0-	100
26	Barbed Wire Fence	21,000 LF	0.71	14,910	19,229	13,652.59	-0-	-
27	12' B/W Swing Gates	4 Ea.	123.00	492	4	492.00	-0-	100
28	60" RCP Sewer	221 LF	46.50	10,276.50	221	10,276.50	-	-
29	Outfall Sewer Manhole	1 Ea.	765.00	765	1	765.00	-0-	100
30	12" CMP	100 LF	6.13	618		618.00	-0-	100
31	24" CMP	70 LF	8.60	602		602.00	-0-	100
32	Remove Exist. Pump Pacs.	LS		10,000			10,000.00	-
33	Service Vehicle #1	1 Ea.	2,900	2,900		2,900.00	-0-	100
TOTAL OF COST COLUMNS								

LINE NO.	DESCRIPTION OF ITEM	CONTRACT			COMPLETED TO DATE		COST OF UNCOMPLETED WORK	% COMPLETED
		QUANTITY	COST PER UNIT	TOTAL COST	QUANTITY	TOTAL COST		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
34	Service Vehicle #2	1 Ea	2,800	2,800		2,800.00	-	100
35	Boat, Motor & Trailer	1 Assy.		840		840.00	-	100
36	Trailer Mtd. Elec. Plant	1 Assy.		2,300		2,300.00	-	100
37	Pond Effluent & Drainage Works							
	a. Struc. Exc. & Backfill	16,400 CY	2.20	36,080		36,080.00	-	100
	b. Concrete Work	1,266 CY	171.00	216,486		216,486.00	-	100
	c. Piping							
	1) RCP	380 LF	23.20	8,816		8,816.00	-	100
	2) W/S	540 LF	78.50	42,390		42,390.00	-	100
	3) Other Underground	1,090 LF	6.50	7,085		7,085.00	-	100
	4) Chlorine	LS		1,906		1,906.00	-	100
	d. Equipment							
	1) Effluent Pumps	3 Ea	13,000	39,000		39,000.00	-	100
	2) Other Pumps			7,000		7,000.00	-	100
	3) Flap Gate	1 Ea	2,900	2,900		2,900.00	-	100
	4) Slide Gates	3 Ea	3,795	11,385		11,385.00	-	100
	5) Chlorination Equip.	LS		27,207		27,207.00	-	100
	6) Chlor. Cyl. Hoists	2 Ea	2,094	4,188		4,188.00	-	100
	e. Electrical							
	1) Underground Conds.	1,240 LF	4.00	4,960		4,960.00	-	100
	2) Above Ground "	1,160 LF	2.00	2,320		2,320.00	-	100
	3) Wire & Cable	21,180 LF	0.20	4,236		4,236.00	-	100
	4) MCC	3 Ea	5,728	17,184		17,184.00	-	100
	5) Fixtures	26 Ea	72.00	1,872		1,872.00	-0-	100
	6) Finish	15 Ea	25.00	375		375.00	-0-	100
	f. Plumbing	LS		2,008		2,008.00	-	100
	g. Ventilation	LS		924		924.00	-0-	100
	h. Sheet Metal	LS		1,168		1,168.00	-0-	100
	i. Structures & Misc. Metals							
	1) Monorail & Bents	LS		2,631		2,631.00	-	100
	2) Handrail	LS		2,177		2,177.00	-	100
	3) Grating & Frames	LS		361		361.00	-	100
	k. Paint	LS		3,500		3,500.00	-0-	100
	l. Roof	LS		1,250		1,250.00	-0-	100
38	Recirculation Pump Station							
	a. Struc. Exc. & Backfill	7,800 CY	3.15	24,570		24,570.00	-	100
	b. Concrete	1,240 CY	182.00	225,680		225,680.00	-	100
	c. Equipment							
	1) Recirculation Pumps	4 Ea	33,250	133,000		133,000.00	-	100
	2) Flap Gates	4 Ea	2,860.75	11,443		11,443.00	-	100
	d. Electrical							
	1) Underground Conds.	1,100 LF	4.00	4,400		4,400.00	-	100
	2) Above Ground "	1,059 LF	2.00	2,118		2,118.00	-	100
	3) Wire & Cable	12,830 LF	0.20	2,566		2,566.00	-	100
	4) MCC	2 Ea	5,728	11,456		11,456.00	-	100
	5) Fixtures	29 Ea	72.00	2,088		2,088.00	-	100
	6) Finish	25 Ea	25.00	625		625.00	-	100
TOTAL OF COST COLUMNS								

ITEM NO.	DESCRIPTION OF ITEM	CONTRACT			COMPLETED TO DATE		COST OF UNCOMPLETED WORK	%
		QUANTITY	COST PER UNIT	TOTAL COST	QUANTITY	TOTAL COST		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	e. Plumbing							
	1) Rough	LS		3,596		3,596.00	-	100
	2) Finish	LS		1,420		1,420.00	-	100
	f. Ventilation	LS		500		500.00	-	100
	g. Sheet Metal	LS		284		284.00	-	100
	h. Struct. & Misc. Metals							
	1) Handrail	LS		1,830		1,830.00	-	100
	2) Grating & Frames	LS		2,075		2,075.00	-	100
	3) Misc.	LS		845		845.00	-	100
	4) Trash Rack	LS		3,981		3,981.00	-	100
	j. Paint	LS		4,510		4,510.00	-	100
	k. Roof	LS		1,250		1,250.00	-	100
	l. Prefabricated Building	LS		10,000		10,000.00	-	100
	m. Masonry	LS		2,000		2,000.00	-	100
	n. Carpentry & Furnishings	LS		10,537		10,537.00	-	100
39	Pilot Plant							
	a. Foundation	20 CY	150.00	3,000		3,000.00	-	100
	b. Equipment & Piping	LS		44,698		44,698.00	-	100
	c. Paint	LS		890		890.00	-	100
	d. Electrical	LS		800		800.00	-	100
40	Contingency			20,000		-	20,000.00	-
TOTAL OF COST COLUMNS				2,166,999.50	2,145,410.12	-		99.4%