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**Department of Energy
Pittsburgh Energy Technology Center.**

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SYSTEMS AND ECONOMIC ANALYSIS OF MICROALGAE PONDS FOR CONVERSION OF CO₂ TO BIOMASS

Covering the Period of September 15, 1993 - December 15, 1993

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SUMMARY OF FIRST QUARTER ACTIVITIES

This first quarter of this project, extending from September 15, 1993 to December 15, 1993 was primarily devoted to initiate this project. General activities included the hiring process for Dr. John R. Benemann, the key staff person on this project, the recruitment of two graduate students (Mr. Bailey Green, of U.C. Berkeley, Energy and Resources Group, and Mr. Blake Tresan, of U.C. Davis, Dept. Civil Engineering) to assist in this project, and organization of library and file information for this project.

One specific activity was the attending by the P.I., Dr. Benemann and the graduate students of a Conference in Berkeley on microalgae for waste treatment and water reuse, at which several papers were presented by this group. Significant information of interest to this project was developed at this meeting and will be used in the analysis to be carried out.

Other specific activities carried out during this quarter included the writing of a draft version of Volume I., Section A of the report and starting work on Sections B and C. A Summary of the project, and a tentative Table of Contents for the Final Report are included in the next Section. These contents will be modified according to progress and developments. Drafts of Sections I.A.1-4 are included in this report.

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SUMMARY AND OUTLINE OF PROJECT

A. PROJECT SUMMARY

Microalgal cultivation is the only photosynthetic process likely to directly utilize power plant flue gas CO₂ for production of biomass, which can be converted into substitutes for fossil fuels, thus reducing atmospheric CO₂ levels and the potential for global warming. Previous economic analyses of such concepts have been based on a number of favorable technical and site-specific assumptions, and concluded that the large-scale (1,000 ha; 100,000 mt/y) production of microalgae could be feasible technically, and could be economically competitive where low cost CO₂ was available, land and climatic conditions favorable, and if fossil fuel costs were at least twice current prices. These prior studies had many limitations: mass balances and cost estimates were uncertain, designs not sufficiently detailed; and the interface between the power plant stack gases and the microalgae production systems not addressed. Many of the scientific and engineering assumptions made in these studies require justification. For example, very high productivities were assumed, but how these were to be achieved was not detailed. Since these studies, considerable experience has been gained in commercial microalgae production, and advances have been made in a number of fields related to this subject. This project will carry out and document a detailed feasibility and economic analysis of microalgae systems for CO₂ capture from coal-fired power plants.

B. FINAL REPORT OUTLINE:

The Final Report will consist of two volumes: Vol. I. Systems Analysis, to develop the fundamental information used in Vol. II. Economic Analysis, containing the engineering designs and costs estimates. A tentative Table of Contents is as follows:

Vol. I. Systems Analysis

A. Introduction and Project Objectives

B. Microalgae Biomass Production Technologies and CO₂ Utilization Projects

1. Current Commercial Microalgae Systems
2. Microalgae Waste Treatment Systems
3. Historical Development of the Concept Microalgae CO₂ Utilization.
4. DOE Program for Algal Mass Culture for Fuels during 1970's.
5. European Program for Algal Biomass Production during 1970's-1980's.
6. DOE Aquatic Species Program, 1980 - 1990
7. Japanese CO₂ Mitigation Projects during 1990- present.
8. Recent U.S. R&D in CO₂ Microalgae CO₂ Utilization, 1990 - present.

C. Physiological/Genetic Factors Limiting Algal Biomass Productivity:

1. Theoretical and Practical Limits to Productivity.

2. Flashing Light Effects and the Light Saturation.
 3. Respiratory Losses (Photo/dark respiration; losses and mitigation).
 4. CO₂ Utilization (Low CO₂ pathway, pCO₂ and pH fluctuations ...).
- D. Species Control in Open Pond Cultures:
1. Species Succession and Competition.
 2. Biological Agents (Rotifers, other grazers, bacteria, etc.).
- E. Maximizing Desired Microalgae Products:
1. Effects of N limitation on Lipid/Carbohydrate production.
 2. Effects of other Nutrient and Environmental Factors.
 3. Genetic improvements for Product Maximization.
- F. Pond Engineering and Design:
1. Fundamentals of Photobioreactor Designs, Deep vs. Shallow Ponds.
 2. Alternative Production Systems (Attached growth, Enclosed Reactors)
 3. Construction Technologies (grading, sealing, berms, scale).
 4. Hydraulics/ Mixing (mixing options, solids suspension, wind, etc.).
 5. CO₂ Supply, Transfer, Storage (Alkalinity, pH fluctuations, etc.).
- G. Microalgae Pond Model
1. Mass and Heat Balances
 2. Average / Extreme Diurnal and Seasonal Fluctuations.
 3. Use of Model for Input Parameters Derived from Prior Sections.
- H. Low Cost Microalgae Harvesting Technologies:
1. Basic and Applied Aspects of Bioflocculation;
 2. Applied Autoflocculation (Brackish and Seawater); and
 3. Other Potential Low-cost Harvesting Processes.
- I. Processing of Microalgal Biomass
1. Conceptual Processes for Extraction of Lipids Fuel Conversion
 2. Alcohol Fermentations of High Carbohydrate Algal Biomass; and
 3. Methane Fermentations Technologies and Nutrient Recycling.
- J. Utilization of CO₂ from Flue Gas and pure CO₂.
1. Effects of flue gas contaminants and utilization.
 2. Optimization of CO₂ transfer into ponds and minimizing outgasing.
 3. Integration with Power Plant Design, NO_x/SO_x Controls, Hg, etc.
- K. Resources, Environmental Impacts
1. Resources Assessment (location, climate, potential sites);
 2. Environmental Impacts (integration with wastewater treatment)
 3. CO₂ Mitigation Analysis (energy balances, gross and net;

The objective in each of the above topics is to highlight data of significance to this project, provide a documented analysis and evaluation of the state-of-the-art, extrapolate scientific and engineering knowledge for a longer-term R&D program, and develop specific parameters that would constrain the designs and cost analysis. A major objective would be to develop design criteria for both a Near Term Design (achievable with < 10 yrs R&D), and a Long-Term Design (> 20 years), with more speculative assumptions and extrapolations. One major differences between these two designs will be productivity. Other input parameters and design specifications for Vol. II will be selected based on the information developed for Volume I.

Vol. II. Cost Analysis

A. Review of Prior Cost Analysis and Cost Methodologies:

1. Review of Prior Cost Analysis of Microalgae Production Systems.
2. Selection of Cost Methodologies used in this Report.
3. Documentation of Capital and Operating Cost Data.

B. Base Line Designs (Near-Term and Long-Term) Parameters and Assumptions:

1. Fundamental Parameters (Productivities, CO₂ and water resources).
2. Basic Pond Design (type, mixing, depth scale). Raceway vs. Deep Ponds.
3. Nutrient and Water Supply/Discharge System (dilution, CO₂ supply).
4. Harvesting Technology (self-flocculation, with(out) centrifugation...)
5. Selection of Processing Options (methane, oils, ethanol, others).
6. Mass and Heat Balances (from Pond Model, also for flue gas)

C. Engineering Specifications and Capital Cost Estimates for both Base Case Designs:

1. Site Preparation (grading, stability and re-grading needs).
2. Pond Designs (berms, materials, construction, erosion, sealers).
3. Water Supply (pipes/channels, storage, elevations, flows,...)
4. Mixing Systems (paddle wheel designs, flow control, hydraulics);
5. CO₂ Supply and Transfer System (flue gas and pure CO₂).
6. Integration with Power Plant (pipeline and blowers, scrubber costs).
7. Harvesting systems (with and without centrifugation)
8. Processing systems (methane, oils, alcohol, other chemicals).
9. Waste Treatment systems (amount and disposal manner of wastes).
10. Support Systems (fertilizers, Buildings, roads, fences, electrical, etc.).

D. Operating and Total Process Costs:

1. Operating Costs by Subsystems: labor, power, materials, supplies, etc.
2. Total Operating costs including indirect costs, capital charges, etc.
3. Overall Process Energy and CO₂ Balances, Final CO₂ Mitigation Costs.

E. Conclusions:

1. Near and Long-Term Potential of Algal Biomass for U.S. Coal-Fired Plants
2. Research Needs Assessment.

VOLUME I. SYSTEM ANALYSIS

I.A. INTRODUCTION, BACKGROUND AND PROJECT OBJECTIVES

I.A.1. INTRODUCTION

Reducing atmospheric CO₂ increases is required to forestall potentially catastrophic consequences of the greenhouse effect. Although the possible consequences are uncertain, reducing the current and projected rise in atmospheric CO₂ levels is a prudent course of action. Natural processes, including oceanic uptake and northern forest sinks, already remove 50 to 60% of anthropogenic CO₂ emissions. A 25% reduction in current CO₂ emissions would, therefore, slow atmospheric CO₂ increases by 40% to 50%. Such a reduction in future atmospheric CO₂ increases would reduce, by almost an order of magnitude (Benemann, 1992), the probabilities of future extreme climatic changes, which are of greatest concern. Thus, even a relatively modest reduction in atmospheric CO₂ emissions could have a very large effect in reducing the potential impacts of future climatic changes. This is a central argument in favor of developing technologies for CO₂ mitigation.

Fossil fuel-burning power plants generate 25-30% of all fossil fuel derived CO₂. Thus they are a major target in reducing CO₂ emissions. Of the many methods for reducing the emissions from fossil fuel-fired power plants, the most expensive appear to be the direct recovery of CO₂ from flue gases, and actually increase their subsequent sequestration in a long-term storage (depleted gas wells, aquifers, oceans, etc.). Chemical scrubbing processes are much more expensive than, for example, remotely sited forestry plantations (which would absorb CO₂ at much lower cost) (Benemann, 1994). Recent cost analyses conclude that stack gas scrubbers for CO₂ could approximately double current electricity costs, and the amount of fossil fuel used, due to high parasitic power consumption (MIT, 1992; Johnson et al., 1992; IEA, 1992). And CO₂ removal is only the first step: the ultimate disposal of the CO₂, into the ocean depths, or depleted oil and gas wells, would add even greater costs (Herzog et al., 1991; Fluor Daniels, 1991).

Photosynthesis is already a major world-wide source of fuels, supplying about 15% of all primary energy consumption (Scurlock and Hall, 1987). Biomass fuels could displace a significant fraction of fossil fuels if CO₂ mitigation were to become a policy and economic goal. However, only the cultivation of algae, seaweeds and microalgae, can benefit from, actually require, an enriched source of CO₂, such as flue-gas (Benemann, 1992). The seaweeds are easily limited for CO₂ (which diffuses 10,000 times slower in water than in air). Microalgae, due to their much smaller size, are not so easily limited and are, thus, the most likely candidates for a biological CO₂ flue-gas utilization process. An assessment of the technical and economic feasibility of such a process is the overall objective of this project. In this introductory section the background to this subject, including project objectives, is presented. Subsequent sections provide more detailed discussions of these topics.

1A.2. HISTORICAL BACKGROUND TO MICROALGAE CO₂ UTILIZATION

Microalgae mass culture technology has been developed for over 40 years (Burlew, 1953; Oswald, 1988). The first commercial production of microalgae took place in Japan, in the 1960's, with the development of a *Chlorella* manufacturing process. Industrial microalgae production was initiated in the U.S. about a decade ago, with the establishment of three major production facilities, two in Southern California and one in Hawaii. The plants produce the filamentous blue-green alga Spirulina, a source of health foods, pigments and aquaculture feeds, and the green flagellate Dunaliella, a source of beta-carotene. These algae are grown in typically 0.5 ha raceway, shallow (15 - 30 cm depth), paddle wheel mixed (appx. 20 to 40 cm/sec), open air ponds; are harvested by screens or centrifugation, and either dried (Spirulina) or processed to extract beta-carotene (Dunaliella). Similar systems are operating in other countries (Taiwan, Israel, Thailand). However, some plants (one in Mexico for Spirulina production and two in Australia for Dunaliella) utilize a very different technology: deep, large unmixed ponds, for the production of these algae. Commercial production systems for microalgae are reviewed in Section I.B.2. Microalgae are also widely used in waste water treatment, where unmixed deep ponds are generally used, the algal species not controlled, and the biomass produced usually not harvested. However, raceway, mixed, ponds have been applied in wastewater systems, where they allow more efficient treatment (Oswald, 1978, 1988). Pond systems for waste treatment is reviewed in more detail in Section I.B.3.

Thus two radically different microalgae production processes are currently used: raceway, shallow, mixed systems and deep unmixed ponds. A comparison between these systems, from a productivity and cost perspective, is presented in Section I.F.1. To anticipate that discussion, for CO₂ utilization and low cost algal biomass production only raceway, mixed systems can be considered.

The concept of using the CO₂ in power plant flue gases for producing microalgae and converting the biomass to fuel, was first studied over thirty years ago by the P.I. and colleagues at the University of California Berkeley. They proposed using wastewaters as a source of nutrients to grow algae in large open ponds into which flue gas would be injected, harvesting the biomass by settling, digesting it to methane gas which was used by the power plant, and recycling the digester effluents and CO₂ back to the ponds. A laboratory-scale system, including nutrients recycle, was successfully demonstrated (Golueke and Oswald, 1957). An analysis concluded that with favorable assumptions this process could be economically competitive with nuclear power (Oswald and Golueke, 1960). This concept was further developed by Oswald and colleagues during the 1970's, with support of the U.S. Department of Energy (DOE). Conceptual engineering designs and cost studies (Benemann et al., 1978, 1982) supported the conclusion that, in principle, algal biomass cultivation in open ponds could be relatively inexpensive, if certain technical problems could be overcome and uncertainties favorably resolved. The DOE continued to support the development of this technology during the 1980's, as discussed next.

I.A.3. THE DOE -SERI AQUATIC SPECIES PROGRAM

In 1980 the "Aquatic Species Program" (ASP), was initiated at the Solar Energy Research Institute (SERI, now NREL, National Renewable Energy Laboratory). The ASP developed algal systems for the production of liquid transportation fuels (specifically vegetable oils). This program, supported many basic research projects, including isolation of a large number of algal strains and investigation of biochemical and genetic aspects of lipid production in microalgae (SERI 1983, 1984, 1987a,b, 1989; NREL 1992). Three outdoor algal production facilities were supported by the ASP, in Hawaii (Laws et al., 1983, 1986, 1988), California (Benemann et al., 1981, 1983) and New Mexico, where two 0.1 hectare ponds (one lined and one unlined) were operated for two years (Weissman and Tillett, 1989, 1992).

These projects demonstrated the ability to cultivate specific algal strains on fresh, saline, and brackish waters at relatively high productivities. This, together with recent industrial experience in commercial algal production in the U.S. supported the conclusion that large-scale algal cultivation is, in principle, technically feasible.

The ASP also carried out a system analysis (Neenan et al., 1987), mainly addressing conversion of algal biomass to fuels, and supported a more detailed cost estimate of large-scale algae production on purified CO₂ and brackish waters (Weissman and Goebel, 1987). This study supported the earlier conclusion that, in principle, it is possible to produce microalgae in large-scale outdoor ponds at low cost. However, many details remained to be addressed, and little scientific or engineering support for the key assumptions was provided. Estimated costs exceeded fossil fuel prices by a large factor.

Recently the ASP addressed microalgae for CO₂ mitigation (Chelf and Brown, in SERI, 1989). From data for land, saline water, and CO₂ availability in Arizona and New Mexico (Maxwell et al., 1985; Feinberg and Karpuk, 1988), they concluded that "microalgal farms on a large scale could have a major impact on CO₂ emissions from power plants in these two states" (which account for 3.4% of total power plant CO₂ emissions, Winter et al., 1992, personal communication). A preliminary analysis suggested that there are no fundamental mass balance problems with such systems (Chelf and Brown, 1992).

Most of the current work of the DOE-SERI ASP is in the development of genetic systems for microalgae, which are to be applied to the development of superior strains of microalgae. The objective is to develop "biodiesel" from microalgae. However, the budget of the ASP has shrunk by almost 90% over the past decade, and this has severely constrained the ability of this team to advance the state of the art of this technology. A more detailed discussion of the ASP is presented in Section II.B.3.

I.A.4. MICROALGAE CO₂ UTILIZATION IN JAPAN

Microalgae CO₂ utilization research has been emphasized recently in Japan. Miyachi (1991) discussed the microalgae CO₂ mitigation projects being carried out by the new Marine Biotechnology Institute: a study of the enzyme carbonic anhydrase in bicarbonate utilization by microalgae (Dionisiosese and Miyachi, 1991), isolation of high CO₂ tolerant marine microalgae (Kodama and Miyachi, 1991), the use of CaCO₃ precipitating algae for CO₂ utilization, and optical fiber bioreactors. At the same meeting Hanagata et al. (1991) and Utsonomiya et al. (1991), from the Univ. of Tokyo (and collaborating institutions), described another program that also screened microalgae tolerant high levels of CO₂ and studied CO₂ utilization by these algae. Hiwatari et al. (1991) studied the potential of CaCO₃ precipitation by marine algae.

At a recent meeting in Amsterdam, Watanabe et al. (1992) (Central Res. Inst. Electric Power Industry) calculated that almost 10 tons of CO₂-equivalent greenhouse gases would be mitigated per ton of algal biomass produced for food or feed (vs. only about one ton if the algal biomass were only used for fuels). This group also isolated high CO₂ tolerant algae, able to grow under flue gas CO₂ concentrations. Also at Amsterdam, Nishikawa et al. (1992) (Tokyo Electric Power and Mitsubishi Heavy Industries) reported on optical fiber photobioreactors with which they achieved high productivities at high light intensities, demonstrating that the light saturation effect can be overcome, at least in principle. Takano et al. (1992) also recently reported on an optical fiber for CO₂ utilization.

Probably the largest program on CO₂ utilization by microalgae has been carried out for the past four years by the Mitsubishi Heavy Industries Corp., in collaboration with several Japanese electric utilities (Negoro et al., 1991, 1992a,b, 1993). This group used algal strains from the DOE/NREL ASP culture collection, and studied the effects of flue gas and NO_x/SO_x on algal cultures in both the laboratory and outdoor ponds. Although in the laboratory, some inhibition was noted, under conditions of rather large excesses of flue gas (mainly due to acidification of the growth media, although some toxicity of NO_x was also reported), in outdoor ponds no effect of flue gases (vs. pure CO₂) were noted. This group has over the past year reported the successful cultivation over a period of almost one year of algal cultures on flue gases.

The Japanese effort in CO₂ utilization by microalgae represents a major commitment (Myers, 1992). The main program, being carried out by the Research Institute for Innovative Technology (RITE) and the Marine Biotechnology Institute, is focusing (as discussed above) on optical fiber photobioreactors, with the goal of having a test plant running within a decade at a total cost of \$123 million. The Japanese projects in CO₂ utilization with microalgae are further discussed in Section I.B.5.

IA.5. CURRENT MICROALGAE CO₂ UTILIZATION R & D IN THE U.S.

In contrast to the extensive R&D effort in Japan on microalgae CO₂ utilization, current activities in the U.S. are limited. As briefly mentioned above, the ASP program has initiated some activities. At Oak Ridge National Laboratory, Woodward et al. (1992) have studied, Cyanidium caldarium, isolated from Yellowstone National Park, which is able to grow at high temperatures and very low pH (1M sulfuric acid!). They argue that such an alga would be able to withstand the very low pH that would be generated in a culture due to SO_x absorption. They were able to demonstrate growth and oxygen production (evidence of CO₂ fixation) in a simulated flue gas containing 440 ppm SO_x.

A major U.S. study of microalgae for CO₂ utilization was an EPRI (Electric Power Research Institute) supported project in Hawaii carried out by Laws (Laws, 1990; Laws and Berning, 1991). They used seawater (from a deep upwelling pipe) for the cultivation of the marine alga Tetraselmis suecica in four 25 m² outdoor ponds. The ponds were operated at 20 cm depth and 75% of the culture was removed every other day, being replaced with fresh seawater and nutrients. Pure CO₂ was supplied as required to maintain a pH of 7.5. The study included a comparison of paddle wheels with Archimedes screws and propellers; they were all similar in power inputs. Foils placed into the pond to stimulate turbulence increased productivities (see also Laws et al., 1983, 1986, 1988). Productivities were generally lower than in prior studies by this group, about 20 g biomass ash free dry weight/m²/day, possibly due to high respiratory losses.

Laws (1990) concluded that seaweeds were favored over microalgae, as they had somewhat higher solar conversion efficiencies and are easier to harvest. However, energy inputs in seaweed culture are likely to be high and most literature data suggests that seaweeds are less productive than microalgae. Laws (1990) calculated that 20,000 ha (200 km²) would be required to assimilate all the CO₂ from a 1,000 MW power plant. He asked "given this large requirement for land, is the idea of converting CO₂ to biomass via photosynthesis worth pursuing?". However, such negative conclusions may be premature because of the conservative assumptions (2.5% solar conversion efficiency) used. However, this dramatizes the need for very high productivities and large land or surface areas.

DOE PETC (Pittsburgh Energy Technology Center) has supported R&D on CO₂ utilization by microalgae, both in-house and by the DOE-SERI ASP. The in-house work has not been published, and the DOE-SERI ASP studies are only in the initial phases (see above). DOE PETC has also supported a "Research Needs Assessment" of the capture, utilization and disposal of CO₂ from fossil fuel-Fired power plants (MIT, 1993), as part of which a preliminary analysis of CO₂ utilization by microalgae was carried out, based on prior studies discussed above (Benemann, 1993). This is reviewed next.

I.A.6. PRELIMINARY ANALYSIS OF CO₂ MITIGATION WITH MICROALGAE

Table I.A.1 (Benemann, 1992), summarizes a very preliminary cost estimate for a large-scale (> 1,000 ha) microalgae production system for liquid-fuels using flue gas CO₂ from a power plant. With current fossil fuel costs (< \$15/barrel), CO₂ mitigation costs would be about \$40 to 70/ton, depending on the productivity assumption. This cost estimate (based on Benemann et al., 1978, 1982; and Weissman and Goebel, 1987), made numerous favorable assumptions about the engineering and biological aspects of such a system. For example, the growth ponds would be 10 ha "raceways", over ten times larger than current experience. For economy, the ponds would be earthwork construction with a clay sealer. Many aspects of this process require further analysis and R&D. Harvesting involves "bioflocculation", in which the algae spontaneously flocculate and sediment in settling ponds. This is a well known natural process which has been demonstrated in waste grown algae (Benemann et al., 1980). However both the scientific basis and actual experience base with such a process requires analysis. Alternative harvesting processes need to be reviewed. The extraction and processing of the vegetable oils from the algal biomass was cost estimated based on soybean processing; no relevant data for algal biomass was available. The algal oils would be produced by limiting the algal cultures for nitrogen without reducing productivity.

Most important, in Table I.A.1 two different productivities were assumed, about 109 and 219 metric tons/ha/yr, corresponding to 5 and 10% solar conversion efficiencies, for favorable sites in the U.S. The lower productivity is based on extrapolation of present experience, the higher one is the theoretical limit, achievable only if it were possible to develop algal strains with a photosynthetic system with fewer light harvesting pigments, allowing better overall sunlight utilization (Benemann, 1990). If close to such theoretical productivities are indeed achievable, and the other assumptions verified, then such a process could utilize flue gas CO₂ at overall costs significantly lower than other technologies. Also, costs would be greatly reduced if oil prices were to rise in the future.

A major constraint on such systems, besides the R&D issues, is the availability of sufficient land and water near the power plant. A 1,000 MWe power plant would require as few as 6,000 ha (Table I.A.2). Also only 30% of the CO₂ emissions from the power plant could be captured, as the system would be sized to utilize most of the CO₂ produced during peak summer daytime utilization, they can not use CO₂ emissions at night or much of the winter time CO₂ outputs. However, as pointed out in the introduction, such a rate of CO₂ capture would mitigate much of the potential adverse effects of CO₂ released from such a power plant. And the land area required is a small fraction, less than one tenth, that required for remote biomass systems (tree farms). Such systems would provide over 3 million barrels of fuel per year. The assumptions and data on which Table I.A.1 is based are reviewed in Section I.C.

TABLE I.A.1. MICROALGAE SYSTEM CAPITAL AND OPERATING COSTS
(Benemann, 1993; based on Benemann et al., 1978, 1982; Weissman and Goebel, 1987).

PRODUCTIVITY ASSUMED:	Currently	Maximum
(ash-free dry weight)	Projected	Theoretical
Average Daily (ash-free dry weight):	30 g/m ² /d	60 g/m ² /d
Annual ("):	109 mt/ha/yr	219 mt/ha/yr
Barrels of oil/ha-year	380	760
CO ₂ Fixed into Biomass mt/ha-yr	240	480
CAPITAL COSTS (\$/ha):		
Ponds (earthworks, CO ₂ sumps, mixing)	27,500	33,000
Harvesting (settling ponds, centrifuges)	12,500	17,000
System-wide Costs (water, CO ₂ supply, etc.)	30,000	40,000
Processing (oil extraction, digestion)	10,000	20,000
Engineering, Contingencies (25% of above)	20,000	27,500
TOTAL CAPITAL COSTS (\$/ha)	100,000	137,500
OPERATING COSTS (\$/ha/yr):		
Direct Costs (Power, nutrients, labor, OH, etc.)	10,000	15,500
Annualized Capital Costs (0.2x Total Capital)	20,000	27,500
Credit for methane produced	- 3,000	- 6,000
Credit for oil produced (\$25/barrel)	-9,500	-19,000
Net Operating Costs \$/ha/yr	17,500	18,000
CO ₂ Mitigation Costs (\$/mtCO ₂)	70	40

TABLE I.A.2. LAND REQUIREMENTS FOR ALGAE CO₂ UTILIZATION

Assumptions: 30% CO₂ average annual CO₂ utilization
 1,000 MW power plant, 0.88 kgCO₂/kWh (Herzog et al., 1991).
 Composition (Ash-free): 50% lipid, 25% carbohydrate, 25% protein.
 Heat of Combustion: 7.5 Kcal/g (60% C in biomass).
 Avg. Annual Solar Insolation: 500 Langleys, 45% visible.
 Production: 1.05 x 10⁶ mt/yr biomass; 3.7 x 10⁶/yr barrels oil.

Annual Productivity mt/ha/yr	109	219
Lipid fuels barrels/ha/yr	380	760
Solar Conversion Efficiency (appx.)	5	10
Fixation C mt/ha/yr	66	131
LAND AREA REQUIREMENTS:		
,000 Ha required growth ponds area	9.6	4.8
,000 Ha total area (ponds x 1.25)	12	6

I.A.7. CURRENT STATE-OF-THE-ART OF MICROALGAE CO₂ UTILIZATION

If the, rather preliminary, economics in Table I.A.1 could be substantiated and achieved, such a process would, indeed, be of lower cost than those projected for chemical-physical processes for CO₂ sequestration and disposal (e.g. an amine scrubber followed by ocean disposal).

Due to climatic, land, and water resources restrictions, the maximal amount of fossil fuel derived power plant flue-gas CO₂ would, in the U.S., be restricted to a relatively small fraction of the total, probably about 5% (Benemann, 1993). It has been argued that such a relatively low potential for CO₂ mitigation does not justify further development of this technology (MIT, 1993). However, there are several arguments in favor of microalgae CO₂ utilization technologies. First, the relatively more favorable economics of algal technologies (based on the assumption in Table I.A.1), would justify at least some attention to this technology. Further, the overall costs of developing microalgae systems are probably much lower than those for technologies with larger impacts. For example, although indirect biological processes (e.g. trees) could have larger impacts and lower costs than microalgae systems, the complexity of such processes requires R&D efforts at hundreds of sites. Microalgae systems are more predictable and, thus, would require less effort for development.

Furthermore, it would be possible to expand the potential resource base by using a two-stage process, for two stage CO₂ sequestration-utilization process. In such a process, the CO₂ from the power plant flue gases would first be scrubbed and concentrated with a conventional process (e.g. amine scrubber), and then transported to a suitable site for microalgae production. This would be comparable to "conventional" processes, involving a separation-transportation-disposal (into deep oceans, depleted gas wells, etc.). In this case the potential of such algal systems would be much larger, probably similar to the potential of other remotely sited disposal options. One of the objectives of the present effort is to analyze this option in some detail. For example, when using concentrated CO₂ microalgae costs would be significantly reduced.

In conclusion, it is premature to dismiss microalgae systems due to perceived limitations, particularly in comparison with concepts whose scientific feasibility and are not yet established and for which not even preliminary cost estimates are available. The conclusion of the summary analysis presented in Table I.A.1, and preceding analysis starting with Oswald and Golueke (1960), was that although much R&D is still needed, no insurmountable problems are apparent and no scientific "breakthroughs" (assumptions without sufficient scientific foundation) are required. If such a cost estimate could be substantiated as a reasonable goal for a long-term (20 year horizon) research program, then this technology could have a role to play in any future management of the CO₂ problem. The objective of this project is to analyze in more detail the cost analysis presented in preliminary form in Table I.A.1.

1A.8. OBJECTIVES AND CONTENTS OF THIS REPORT

The scientific and engineering foundations of low-cost, large-scale microalgae production, although greatly advanced over the last 40 years, have not been sufficiently developed, and documented previously, to allow for independent review and analysis. The objective of the present study is to allow for such an independent assessment, and to focus attention on the key scientific and engineering problems that need to be resolved before the feasibility of this technology can be established.

Many aspects of large-scale microalgae production are still subject to uncertainty, speculation, and unproven assumptions, requiring more analysis, research, and development, if highly productive and low cost systems are to be achieved. A sampling of major issues that are addressed in the present Report are:

- How to select and develop microalgae strains suitable for algal mass culture.
- How to produce microalgae biomass with a high lipid content at a high productivity.
- How to overcome light saturation and minimizing respiratory losses.
- How to control and use bioflocculation or other similar harvesting processes.
- How to maximize CO₂ utilization (supply, transfer, utilization, outgasing, etc.).
- How to design large-scale ponds (mixing, sealing, water management, etc.).

As already stated, microalgae culture is an established industrial activity in the U.S., but at a scale and at a cost that differ, in productivities, scale and costs, by an order of magnitude from those required for CO₂ utilization. However, these commercial systems already have demonstrated the basic elements of an algal mass culture system: open, shallow, raceway, paddle wheel mixed ponds. The fundamental issue is whether through improvements in such designs, the selection and cultivation of more stable and highly productive species, development of lower cost harvesting and processing technology, increases in scale, selection of favorable sites, and other process improvements, it will be possible to reduce costs sufficiently to allow cost-effective CO₂ utilization and biomass fuels production. Although the above preliminary analysis suggested that this may be feasible in principle, many aspects of the production process remain to be addressed and examined for their fundamental limitations and potential for improvements.

For example, alternatives to the shallow, mixed raceway pond could be considered: Deeper, unmixed ponds are also used in microalgae production. However, such systems, although of lower cost, have limitations, which reduce achievable productivities. This, however, has not been well documented. An analysis is presented in Section I.F.2. Various mixing methods can, and have been, proposed and used. Paddle wheel are energy efficient, low cost, and flexible. However, other mixing methods have been proposed for large scale systems: Archimedes screws, to low-head pumps, air-lifts and "mixing board". These are reviewed in Section I.F.3.

Shallow pond systems have the advantage of higher cell concentrations, and are of lower cost than deeper ponds. However, deep ponds have higher CO₂ storage

capacities and exhibit lower diurnal temperature fluctuations. Among factors which determine optimal depth are alkalinity, pH range of operations, scale of ponds, construction costs, cost of CO₂ transfer, outgasing coefficients (O₂, CO₂), local climate, cost of berms around the ponds, etc.. These in turn are interactive and also dependent on other factors. A "Pond Model" (Benemann and Tillett, 1990) has been adapted to the present study to allow optimization of input parameters (Section I.G.)

A major issue is the efficiency of CO₂ utilization, which depends on both the transfer efficiency and outgasing from the ponds. Outgasing in turn depends on the pH, alkalinity, and mixing velocity (or, more accurately, turbulence in the ponds, which also is dictated by bottom roughness and depth, among others). There is an extensive literature in this field which requires review and analysis (Section I.F.4).

The selection of algal strains able to be cultivated with minimal invasions, grazing, and other upsets is required. The management of the biotic environment in outdoor ponds requires much further analysis. Both the theoretical and practical aspects of this problem must be addressed. A major issue is how to select suitable algal species and strains. In the longer term, genetic improvements could be achieved using the tools of genetic engineering. These issues are reviewed in Section I.D.

The microscopic nature of the algae, and the dilute nature of their culture, makes harvesting a major technical (e.g. cost) issue. Harvesting of microalgae has been the subject of a large number of studies reviewed in Section I.H. Bioflocculation is the harvesting technology assumed in Section I.H and has been demonstrated experimentally at the 0.1 ha scale with waste treatment ponds (Benemann et al., 1980). However, such processes are presently mainly observational, lacking sufficient experimental and theoretical data and analysis. An extensive ecological and physiological literature, both in the microalgae and related (e.g. yeast, bacteria) fields is reviewed to provide a mechanistic basis for such processes and guide future R&D development. Also, the availability of cationic polymers may now allow a more cost-effective algal harvesting with such agents. Centrifugation is used as a final concentration step for the biomass, adding over 10% to overall costs. It may be possible to substitute a lower cost secondary gravity settling process, depending on the biomass to fuel conversion step. (See Section I.H.)

The technologies for converting algal biomass to fuels have not been sufficiently addressed in prior analysis. If ethanol or oil are the desired products, then algal biomass high in carbohydrates or lipids, respectively, must be produced, without loss in overall productivity. The ability to produce high lipid or carbohydrate biomass at high productivity is probably one of the more difficult issues in this field. Laboratory data and the underlying biochemical/physiological mechanisms are reviewed. Some algae produce large amounts of fuel products: Botryococcus braunii can produce over 50% of an essentially diesel fuel quality hydrocarbon. How to couple this metabolic capability with fast growth and high productivity will be a challenge which could be solved with genetic technologies. (See Sections I.E and I.I.)

Algal productivities achieved by outdoor microalgae cultivation systems have been generally about 3 to 4% of total solar in the best cases for larger systems on a year-round basis. A 5% conversion efficiency could be extrapolated as being achievable in the near-term (< 10 years), based on favorable assumptions. However such conversion efficiency are well below the 10% conversion efficiencies projected from theoretical models and observed in laboratory cultures under low light intensities. Although many factors limit productivities in outdoor systems, the major one is the phenomenon of light saturation. In principle light saturation could be overcome through regulation of the photosynthetic apparatus such that the light harvesting:reaction center pigments ratio is reduced. How to achieve this in practice has not yet been addressed. How to regulate respiration in ponds so as to reduce losses of photosynthetic products is another fundamental physiological-biochemical problem of great importance. The potential mechanisms by which these limits could be overcome are discussed in Section I.C.

In the ponds the pH and $p\text{CO}_2$ will fluctuate, depending on a number of design parameters (e.g. number and distance of carbonation stations). This requires a more fundamental analysis in terms of $\text{CO}_2/\text{HCO}_3^-$ utilization by algae and adaptations to various CO_2 regimes. Another fundamental issue in the utilization of flue gas CO_2 by microalgae is the potential for toxicity by flue gas contaminants - SO_x , NO_x , organics, trace metals. NO_x is a problem in greenhouses fertilized with CO_2 from fossil fuel combustion (Hand, 1990). There is only limited literature on the use of combustion flue gases in algal mass cultures, with ongoing work in Japan and some work starting at NREL and PETC. This and other data are reviewed (Section I.B) and detailed mass balances presented, concluding that it is indeed be possible to cultivate algae on coal-fired power plants flue gases (Section I.J).

For a 1,000 MW power plant a total land area of at least 70 km^2 (appx. 27 mi^2) would be required, and probably somewhat larger, located in the immediate vicinity of the power plant. Finding suitable land and water resources for microalgae systems requires consideration of many factors (Vigon et al., 1982).

In practice, an important question is how to interface the power plant flue gas discharge with the piping and distribution system supplying CO_2 to the algal ponds. One problem is whether the flue gas requires cooling for optimal distribution. Benemann et al. (1982), on which the above cost estimate (Table I.A.1) is based, did not consider this issue and it requires further study. Flue gas distribution and supply must be the subject of a "ground up" engineering design and cost estimate.

Indeed, the overall objective of this project is to provide such a "from the ground up" engineering and cost analysis of all aspects of this technology. The above listing of issues considered in such an analysis provide the basic inputs to such a feasibility study, the Subject of Volume II of this Report.

I.B. OVERVIEW OF CURRENT MICROALGAE PRODUCTION

I.B.1. INTRODUCTION

Microalgae production combines plant photosynthesis with characteristics of microbial fermentations: high growth rates and hydraulic production systems. Microalgae can be grown in the dark on sugars and other carbon substrates, and several fermentative production processes have been developed for vitamins, food supplements, and animal feeds. However, only "photoautotrophic" production systems, that use sunlight and CO₂ as energy and C sources, are considered here.

Microalgae production R&D was initiated forty years ago, with the goals of human food production (Burlew, 1953) and wastewater treatment (Oswald and Gootas, 1953). Over the past four decades microalgae production has been investigated in many countries for these and many other applications: animal waste treatment, fuels production, heavy metal sequestration, atmosphere regeneration in space vehicles, fertilizers, xanthophylls (pigments useful in animal feeds), omega-3 fatty acids, amino acids and vitamins, diagnostic reagents, surfactants, industrial polysaccharides and other specialty chemicals. The biotechnology of microalgae production has been reviewed in several proceedings, books and reviews (Soeder, 1978; Shelef and Soeder, 1980; Becker, 1985; Barclay and McIntosh, 1986; Terry and Raymond, 1985; Richmond, 1986a,b; Benemann et al., 1987; Borowitzka and Borowitzka, 1988; Lembi and Waaland, 1988; Richmond, 1987; Cresswell et al., 1989; Vonshak, 1991; Tredici and Masserati, 1992).

The major practical application of algal pond cultures thus far has been in the field of wastewater treatment. However, in such ponds algal species are not controlled and the biomass is seldom harvested. The first large-scale (> 1 ton/month) commercial microalgae production, of the single cell green alga Chlorella, was established in Japan during the early 1960s. Chlorella is sold as food supplements ("health foods"), and most production is currently located in Taiwan. Production of the filamentous blue-green alga Spirulina, a traditional food in several countries, was initiated in Mexico about 1974, and is now also being produced in the U.S., where two large (> 200 tons/year) production plants are operating in California and Hawaii. Spirulina, which favors high bicarbonate environments, is sold as a food supplement, to extract a blue food color, phycocyanin, and in specialty aquaculture feeds. The third microalga produced commercially is the green alga Dunaliella, which grows in hypersaline environments and contains large amounts of beta-carotene, a food color and reputed anticancer agent.

In this report only applications that can result in significant CO₂ utilization are considered, which effectively restricts attention to fuels production, possibly in combination with waste water treatment. Commercial applications of microalgae culture are considered as models for future large-scale low-cost production systems. Existing technology and state-of-the-art in these areas is reviewed in this section.

I.B.2. LARGE-SCALE COMMERCIAL MICROALGAE PRODUCTION

As mentioned above, starting in the early 1960's several production facilities were established in Japan for Chlorella production. Chlorella is marketed as a food supplements, mostly in pill form. The initial systems consisted of shallow circular ponds, but by the early 1970's a paddle wheel mixed, raceway pond design, developed in the U.S. and Germany, was adopted (Figure I.B.1). Major problems with the production of Chlorella are the ease of contamination of the cultures (requiring large amounts of inoculum) and the high cost of harvesting with centrifuges. Some plants use "mixotrophic" growth, in which the algae were grown with acetate (rather than CO₂) as a source of C and also energy, reducing light requirements. Chlorella has also been produced in dark fermenters, followed by a brief exposure to light (to induce pigments). By the mid 1970's about 40 plants, most located in Taiwan (where the climate is better than in Japan), were operating with an annual production of almost 1,000 tons. Since then there has been considerable consolidation, with less than ten plants producing somewhat above 500 tons of dry Chlorella annually. Major companies are Taiwan Chlorella Manufacturing, Tunghai Taiwan, Far East Microalgae, and China Chlorella. Production costs are high and wholesale prices about \$25,000/ton.

Spirulina, a filamentous blue-green alga, requires high (> 15 g/l) bicarbonate medium, but is easier to produce than Chlorella since it is resistant to contamination and can be easily harvested by screens. Table I.B.1 lists current production facilities. Smaller units (< 10 ton per year) are operating in India, Brazil, and Argentina and a new plant in Thailand is reportedly using farm wastes. In China several plants are reported to be operating, producing several hundred tons, but no specific information is available.

Table I.B.1. SPIRULINA PRODUCTION FACILITIES

Company	Location	Area ha	Production tons/year Actual/Capacity	System Design
Earthrise Farms	So. Calif	8	250/300	Raceway
Cyanotech	Hawaii	4	150/200	Raceway
Siam Algae	Thailand	4	100/150	Raceway
Sosa Texcoco	Mexico	33	300/1000	Deep Pond
Blue Continent	Taiwan	10?	100?/300	Raceway
Nippon Spirulina	Japan	1.5	30/?	Raceway?

Most production systems use the paddle wheel mixed, plastic lined, shallow (< 30 cm) raceway pond design, which allows good control over conditions (such as CO₂ supply). Individual growth ponds are up to about 0.5 ha in size, although larger sizes are feasible. Earthrise Farms operates one approximately 3 ha pond, which is unlined. In these ponds Spirulina is normally grown as a continuous culture (vs. batch cultivation for Chlorella). The media is almost completely recycled to conserve the expensive bicarbonate. By contrast, the plant in Mexico relies on the high bicarbonate waters available at this site and uses a deeper (appx. 1 m), unmixed, single pond (33 ha) for Spirulina production, with little or no CO₂ addition. Spirulina harvesting typically involves fine mesh screens with backwash, followed by some type of vacuum filtration. The algal paste is spray dried.

Three main products are obtained from Spirulina: health foods (powder and pills), animal (mainly aquaculture) feeds, and a food coloring agent (phycocyanin) used in Japan and produced by Dai Nippon Ink and Chemicals Co. (DCI). DCI owns the Earthrise Farms and Siam Algae production facilities indicated above. The amount of Spirulina used for phycocyanin extraction, aquaculture feeds, and other animal feeds are approximately 100 tons each. About 600 tons are being sold for health foods. Production costs for U.S. systems are probably about \$10,000/ton (dry weight powder), with wholesales prices of about \$20,000/ton. Production costs for the Mexican plant are probably less than half U.S. plant costs. Current Spirulina production could be significantly expanded from existing production systems.

Dunaliella, a motile green alga that lacks a rigid cell wall, is cultivated in high salt brines for the production of beta-carotene (b-C). In the U.S. Dunaliella is cultivated in high rate ponds, similar to those used for Spirulina production. Dunaliella contains about 3 to 5% of dry weight natural beta-carotene, a vitamin and antioxidant, with reputed anticancer activity. The synthetic product costs about \$500/kg, the natural algal product sells for about \$1,500/kg (on a beta-carotene content basis). The product is sold either as a dried powder or encapsulated vegetable oil extract. Table I.B.2 lists the major current production plants.

TABLE I.B.2. DUNALIELLA PRODUCTION FACILITIES

Company	Location	Area ha	Production System tons/year b-C	Design
Nutrillite Products	So. Calif	4	2?	Raceway
Nature Beta Carotene	Israel	4	2?	Raceway
Western Biotech	W. Australia	100	2?	Deep ponds
Betatene	Australia	??	2?	Natural Ponds

The production estimates for Dunaliella are very approximate as no direct information is available. The first two plants use paddle wheel mixed, shallow, raceway ponds while the other two use deeper, unmixed ponds. Thus, as with Spirulina and Chlorella, no standard production system has developed in this field. Overall, it would appear that the raceway pond systems have operated more reliably and are more productive, but the relative economics of deep-unmixed vs. shallow-mixed ponds has not been established and are very site specific.

There are a few other commercial microalgae products produced at a small scale. Examples are the cultivation of microalgae for soil and rice paddy inoculation (Phady, 1985), although the effectiveness of such inocula remains to be demonstrated, and microalgae production for aquaculture feeds (Benemann, 1992b). Typically in aquaculture operations small batches of algae, mainly seawater diatoms and flagellates, are produced under highly controlled conditions in translucent cylinders, plastic bags, carboys, or tanks, generally under artificial illumination and/or in greenhouses. Production seldom exceeds 100 kg (dry weight basis) per year per facility. The algae produced are used for feeding bivalve (oyster, clam, mussel, etc.), larvae and "seed", or in the hatchery operations for shrimp and fish (where they are also used to produce zooplankton feeds). The algae are produced as needed, and the live culture used directly, without harvesting or storage.

A few larger companies produce the required algae using indoor and greenhouse deep (appx. 1 m) tanks, often with artificial lights, with total algal (dry mass) production of a few tons per year (Donaldson, 1991). Cost of production even at this scale are high, and have been estimated to be over \$250/kg for an optimized facility (Walsh, 1987). SeaAg, Inc., a private company located in Florida, is currently producing microalgae for bivalve aquaculture in outdoor, paddle wheel mixed, ponds, similar to those used for commercial microalgae production discussed above. The scale of the operation is currently about 500 m², with annual algal production about 2 tons. This technology could be rather easily scaled-up and production costs would be lower than for other commercial systems as the algae would not be harvested or dried, normally the major cost factors in such operations. This process was initially developed as part of a U.S. DOE-SERI funded project for microalgae energy production, and represents an early technology "spinoff" of this program.

In summary, the commercial production of microalgae in the U.S. is currently limited to three relatively large (appx 4 - 5 hectares each) production systems, all using the paddle wheel mixed, shallow raceway pond design. Three smaller production companies produce microalgae for aquaculture in significant (> 1 ton/year) but rather small amounts. It should be noted that there is essentially no technical information published about any of these production systems, as the technologies are considered proprietary.

I.B.3. MICROALGAE WASTEWATER TREATMENT SYSTEMS IN THE U.S.**I.B.3.a. Introduction**

Microalgae are extensively used for municipal and industrial wastewater treatment in the U.S., with about 10,000 pond systems currently operating, most of them quite small. In waste treatment ponds, known as "oxidation ponds", the microalgae provide the dissolved oxygen used by bacteria to break down and oxidize wastes, thereby liberating the CO₂, phosphate, ammonia, and other nutrients used by the algae (Oswald, 1978, 1990). In essence the organic matter in the influent, that which does not settle and decompose in the sediments, is converted into algal biomass by the action of solar energy. Discharge of the pond effluents, containing the algal biomass, results in a suspended solids and BOD load in the receiving bodies of waters, creating potential problems (oxygen deficits, eutrophication), unless the effluents can be greatly diluted. If dilution is not available, the waste treatment pond effluents must be disposed of on land, the algae settled in terminal "settling ponds", or the most expensive option, the algae harvested and disposed of.

It should be noted that there is no effort made to grow any particular species of algae in such ponds. Species control could greatly aid in algal harvesting by favoring filamentous or easily settleable algae (Benemann et al., 1980), but this needs much more research. Most oxidation ponds are relatively deep (typically about 1 - 2 m) and not mixed. However, a few municipal waste treatment ponds use mixed raceway pond designs. Examples of microalgae wastewater treatment ponds in Northern California are listed in Table I.B.4. The mixed raceway ponds do not use paddle wheels, rather relying on recirculation (St. Helena) or Archimedes screws (Hollister). The algal pond systems that harvest the algae use chemical flocculants (lime, alum, polyelectrolytes). None of these pond systems are, however, typical examples, as few other oxidation pond systems use either the raceway ponds or harvest the algal biomass. However, they are of specific interest to the present project, and thus are reviewed in some more detail below.

TABLE I.B.3. EXAMPLES OF MICROALGAE WASTE TREATMENT SYSTEMS IN NORTHERN CALIFORNIA

Location	Area ha	System Design	Algae Harvest/Disposal
Napa	140	Deep Ponds	Harvest Flocculants
St. Helena	8	Raceway (2 ha)	Terminal Settling ponds
Sunnyvale	180	Deep Ponds	Harvest Flocculants
Hollister	13	Raceway (5 ha)	Land Disposal

I.B.3.b. Sunnyvale, California Oxidation Ponds

This treatment plant consists of a set of two large ponds covering a total of 440 acres (one smaller, one larger), currently receiving about 17 MGD (million gallons per day). The depth of the ponds is 3 to 15 feet, and they are very irregular. (These ponds used to be salt evaporation ponds). The ponds have an estimated hydraulic retention time of 13 to 50 days.

The ponds receive primary treated waste water and the pond effluent is treated with flocculants, allowing removal of the algal biomass in a DAF (Dissolved Air Flotation) system. From the DAF system the effluent goes through a dual media filtration (DMF) process consisting of anthracite coal, pea gravel, and sand. This is followed by chlorination and dechlorination, from where the liquid is sent to the San Francisco Bay. The key to the operation of the process is the flocculant used in the algal separation process. Initially, when the plant was first equipped with algal removal facilities in the late 1970's, alum was used as the primary flocculant. This worked relatively well, with the flocculated algal biomass disposed of by recycling to the ponds. Work carried out in the late 1970's demonstrated that alumn flocculated algae do not ferment (Eisenberg et al., 1980). Thus, most of the recycled algal biomass is probably still present in the pond. Starting in the mid 1980's the cationic flocculants were used for algae removal at this plant. The currently used polymer (Diatec of Southgate, California) is a proprietary product. The cost of flocculation is estimated at \$126/MGD, with about \$0.1/lb of liquid flocculant.

The flocculant is diluted 1/10 in mix tanks and then added to the effluent coming into the DAF system at a rate of 10.5 ppm. There has been a continuous improvement in the performance of this system, in terms of reducing residual algal concentrations (measured as turbidity units) over the past decade, as organic cationic flocculants have improved. The goal is to allow up to 25% water reuse of the effluents, for landscaping, golf course irrigation, etc.

Once the polymer emulsion is prepared at the suitable dilution, it is pumped to the DAF unit, where it is injected (via perforated ring) at two sites, one below and one at the zone of decompression. In the DAF process, about 25% of the flow is compressed with air at 80 PSI and allowed to decompress during contacting with the rest of the flow. Although there is great emphasis on the performance on the DAF process, there has been relatively little study of the ponds themselves. The ponds are provided with a set of four 62.5 MGD circulation pumps, and it also receives some mixing from the wind. However, there is little doubt that hydraulics are rather poor, with a rather high dispersion coefficient, and much of the area not used effectively. However, the large area of these ponds (440 acres) makes this not a critical issue.

The ponds produce (at the present time) about 45 ppm of suspended solids (coming into the DAF system), which typically ranges from a low in winter (about 30 ppm) to

a high in summer (as much as, or over, 100 ppm). Thus there is a large variation in the effluents of these ponds. The algae present in the effluents are also very variable. A large variety of microalgae is present, with green algae and euglenoids being very dominant. Species mentioned include Closterium, Cylindrotheca, Euglena, etc. In winter Chlorella is often found (possibly selected by lower pH and higher BOD). Chlorella is difficult to harvest.

Currently the algal biomass harvested by the DAF system is returned in part to the ponds (about 75%), with the rest being subjected to anaerobic digestion in the conventional primary digesters. Eventually most if not all the algal sludge is to be digested, rather than returned to the ponds. (The fate of the digester sludges is unknown). The algal sludge collected by the DAF is returned to the ponds or sent to the digesters by means of an air driven pneumatic system (no moving parts).

This plant is the only current example of algal harvesting and conversion to fuels. The plant has seen many changes over the years. After the installation of the DAF system for algae removal, changes were instituted to allow operation of the process. Thus, the current state of the art is the result of continued development and trial-and-error testing over the past decade. The major advance was the development of the cationic polymers. The applicability of such polymers for the removal of algae from large-scale production systems should be further investigated.

I.B.3.c. Napa, California, Oxidation Ponds.

The Napa ponds consist of a series of four ponds, approximately of equal area, with a total area of about 130 hectares (350 acres). The ponds receive about 15 MGD of primary effluent (e.g. primary treated) mixed with some raw sewage. The influent of the plant is about 320 ppm of suspended solids. Plant effluents average less than 20 ppm. The ponds are operated in series with the first pond receiving the raw sewage, and the last pond discharging into the algae separation plant.

This plant operates with two different discharge systems: irrigation during summer and discharge to the Napa river during winter. Discharge to the Napa river during summer is limited by the low flow of the river, which would not allow sufficient dilution. However, irrigation areas are limited, and thus during summer (even accounting for evaporation) results in an increase in total volume.

These pond systems have had major operating problems over the years, probably due to modifications of the original design, which reduced the initial pond depth from 8 to 4 feet. This shallow depth for the first pond resulted in the accumulation of a sludge layer, which created odor problems. Indeed, the lack of an initial deep pond that would allow anaerobic digestion of the influent (and, thus, remove a large fraction of the influent C) was probably a major design limitation, in that it not only caused odor problems but also excessive algal growth.

From the ponds the effluent is transferred to an algae harvesting system, which consists of a set of four settling chambers, to which long chain cationic polymer is added to flocculate the algae. Initially this plant used mainly lime and some alum. Like The polymers are added in the amounts of 100 ppm for 515C and 2 to 4 ppm for 1596C. The settled sludge is hydraulically pumped back to pond 1. (There used to be separate sludge beds when the flocculant was lime, but now the sludge is discharged back to the initial pond, further compounding the problems of low water levels, odors production and too little carbon destruction).

The algae ponds produce on average an influent to the algae removal system of about 100 ppm, which is reduced by the flocculants and the settling chambers to below 20 ppm. Total cost for the use of the flocculants is about \$150/MGD. There is only a little data on algal counts and identifications. (This data was collected for a couple of years during mid 1980's but not since then). There is a "big difference" in the performance of the algal harvesting process depending on the type of algae coming in" according to the plant operator, but there is no documentation of this (e.g. relating the algal type with process performance).

This treatment plant will be replaced this year with an activated sludge plant. There reason for this is that the ponds are on occasion discharging a relatively high BOD level (a few months last years) and there are also significant odor problems. (Pond 1 has some small surface aerators for this purpose, but they are too small to do any good). Thus, the decision has been made to abandon the pond treatment process in favor of a conventional activated sludge plant. The ponds will be retained for storage of storm flows, and for plant outages, but they no longer will be a part of the treatment process. This pond system is perhaps representative of the problems encountered with conventional oxidation ponds.

I.B.3.d. St. Helena, California, Integrated Ponding System

These ponds receive a relatively small amount of local domestic and some winery waste. The ponds were constructed 25 years ago following a design by the P.I., and are the first (and one of the very few) raceway-type ponds for municipal waste treatment. The dimensions of the ponds are:

TABLE I.B.5. DIMENSIONS OF ST. HELENA, CALIFORNIA PONDS

POND #	SIZE Acres	VOLUME Ac-ft	DEPTH ft
1	2.9	25	10
2	5.1	15	3
3	2.5	17	8
4	4.7	52	13
5	6.3	73	13.5

The influent comes into Pond 1, which is a deep anaerobic pond where there is considerable destruction of solids (and even soluble) BOD. To minimize odors some effluent from Pond 2 (the raceway) is recirculated to the surface of Pond 1. This is now being carried out on the basis of the dissolved oxygen in this fraction. The raceway pond (Pond 2) is currently mixed with pumps, which provide relatively poor hydraulics. They are to be replaced with a paddle wheel later this year. The effluent of Pond 2 is discharged to Pond 3, which is a "maturation" pond and then to ponds 4 and 5, which are "settling" ponds. Then the effluent is discharged, after chlorination, to the Napa River. Some algae will settle in the maturation ponds, but there is also considerable potential for re-growth, and the amount of algal removal is not well established. These latter ponds also serve to equalize flow and to provide holding capacity for when discharge limitation are in effect due to the low level of the river. Relatively little data has been collected about this system over the 25 years of its existence. For example, the nature of the algal species present is unknown.

I.B.3.e. Hollister, California Integrated Ponding System

The Hollister Ponds are the second (after the St. Helena Ponds) integrated ponding system for waste water treatment in California designed by the P.I..

The pond system consists of two primary ponds designed with two depressions in the middle that are supposed to serve as settling and sludge collection sites. These ponds are classified as anaerobic, they are supposed to be maintained odor free through the recirculation of an active culture of microalgae from the high rate ponds (such as also practiced in St. Helena). However, as also in St. Helena, several surface oxygenators (simple floating aerators) provide additional oxygen supply to these ponds, to prevent odors. The operator at this plant stated that without these aerators the odor problem could be severe on occasion.

The high rate pond consists of 16 acres of a serpentine, single channel raceway, with a large number of turns (see figures). The mixing is provided by a set of two large Archimedes screws, of which one is sufficient for providing the required circulation. For the past 18 months the baffles in many of the dividers have been destroyed by the Oct. 1989 earthquake. Despite the extensive short circuiting that this obviously caused in these ponds, there is no indication that this in any way affected operations, according to the operator. The last pond in the series is a small holding pond.

There is no discharge from this plant, the effluent from the high rate ponds is directed to a series of percolation ponds, which recharge the local aquifer. To prevent sealing of the ponds, they are periodically let dry and then disced to break up the top few inches of the surface. However, the percolation ponds have lost a large amount of their percolation capacity, due to excessive algal solids applications.

I.B.3.d. Conclusions and Discussions

Oxidation ponds treat wastewaters by a combined action of:

1. **Aerobic processes:** aerobic bacteria break down wastes and release nutrients (CO_2 , P, N, etc.) used by algae, which in turn provide O_2 for the bacteria.
2. **Anaerobic processes:** the large amounts of suspended that settle to the pond bottoms are broken down by anaerobic bacteria, with the release of methane, CO_2 , sulfides, organic acids and other organic compounds, and various dissolved nutrients. Some of these are oxidized in the water column, others escape, and others assimilated into algal biomass.
3. **Photochemical and chemical processes:** the relatively high oxygen tensions and light intensities (at the surface) result in oxidation processes not commonly found in activated sludge systems. The nature and extent of such reactions are, however, somewhat speculative. One consequence appears to be high disinfection rate of such ponds.

Design criteria for conventional oxidation ponds (also called facultative ponds) are based essentially on rule of thumb of so many kg of BOD (biological oxygen demand) per hectare, adjusted for local climatic conditions (e.g. latitude, temperatures, rainfall, etc.). Although some design efforts based on more fundamental principles have been made (Oswald, 1978, 1990), these involve many assumptions which have only partially been documented.

The unmanaged nature of conventional oxidation ponds, their poor hydraulics and large dispersion coefficients, make such system very unpredictable in such basic performance aspects as solids outputs. Algae biomass, estimated at over 75% of the total solids discharged by such systems, can vary by a factor of ten within a period of a few days, similar to the situation found in eutrophic lakes. Essentially, oxidation ponds are extremely eutrophic systems influenced by similar factors as natural ecosystems. There is no control over algal populations, or even over productivity, and, thus, over system performance.

Once consequence is that the systems have to be designed with an excessive safety factor. As costs are to a large extent land dependent (e.g. economics of scale are low), this raises costs disproportionately for such systems, compared to processes such as activated sludge which can be better predicted in terms of performance.

However, the largest problem with these systems is the large amount of solids (e.g. material recovered by 0.45 μm filters, mostly algal biomass) in the effluents. This has two untoward effects: 1) It makes it difficult to use conventional disinfection (e.g. chlorination) because of the large amount of organic matter represented by these solids (nominally as much as 100 mg/l) and 2) When the algal biomass is discharged into a receiving body of water the algae would, at a minimum, exert a proportional oxygen demand load, and at worst could upset the ecosystem. Overall, discharge of algal solids is not desirable.

Harvesting of the algal biomass is, however, expensive. Centrifugation costs are about \$1,000 per MG and chemical flocculation is only about one third cheaper (when considering the costs not only of the flocculants, about \$150/MG) but also capital costs, maintenance, power, labor, etc.). The experience at both Sunnyvale and Napa with chemical flocculation has not been recorded in the literature. Recent introduction of organic flocculants to replace the inorganic ones (lime, alum, ferric chloride) have improved overall performance, but probably not economics. The literature records dozens of "solutions" to the algal harvesting problem. None have succeeded in the marketplace, thus far. This is further reviewed in Section I.H.

Although algae harvesting is at the crux of this field, the high costs and energy inputs of activated sludge systems, compared to algae systems, assures that even without a satisfactory solution to this problem, such systems could find wide-spread applications, wherever local situations allow water re-use, land is not limiting, and other factors permit the application of any of the above cited alternatives. Even a partial harvesting process could greatly enhance this technology if it improved the resulting effluent sufficiently to meet local needs and circumstances.

One approach, is to make algal treatment system more intensive and predictable, less subject to the whims of nature. Essentially this involves, as a first step, better hydraulic mixing, to allow a more uniform pond environment. For this purpose the high rate ponds, as operating in St. Helena and Hollister, are best. High rate ponds would greatly improve the overall algal productivity in such systems, which would translate to overall oxygen production and, thus to waste oxidation. The trade-off is that much more algal solids would be produced, as much of the productivity in current pond systems settles out and is decomposed anaerobically in the pond bottoms. This makes algae harvesting from such systems even more important.

Although either the energy or plant nutrient values of the algal biomass are not significant economically, there are environmental benefits to the recovery of these materials. The plant nutrients are often major factors in the eutrophication of the environment, and are resulting in stricter rules for the discharge of nutrients by waste treatment plants. Also, methane escaping from the ponds, or generated due to decomposition of released algal biomass or nutrients, is a greenhouse gas. In a properly designed integrated pond systems, with algal recovery, most of the plant nutrients and methane gas could be recovered.

Ultimately the application of this solar energy technology would have significant effects on the overall greenhouse effect: instead of using fossil fuel generated electricity as in the conventional technologies (e.g. activated sludge), would produce renewable energy while also conserving irreplaceable nutrients (e.g. P), at great overall economy. Perhaps most applicable to the present study, waste water could be used as a make-up water and nutrient source for large-scale CO₂ fixation systems, as already suggested by Oswald and Golueke (1960). This is addressed further in Volume II.

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