An extract of a few pages from the
US National Renewable Energy Laboratory's (NREL)
review of its Aquatic Species Program -

carbon dioxide from power stations was fed into
algae ponds to produce biofuels.

Extracted by Colin Dunstan, May 21 2009.

For the complete document, see -

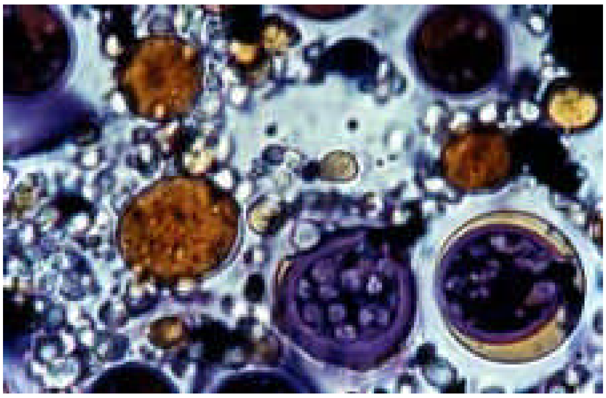
Look back at the U. S. Department of Energy's Aquatic Species Program

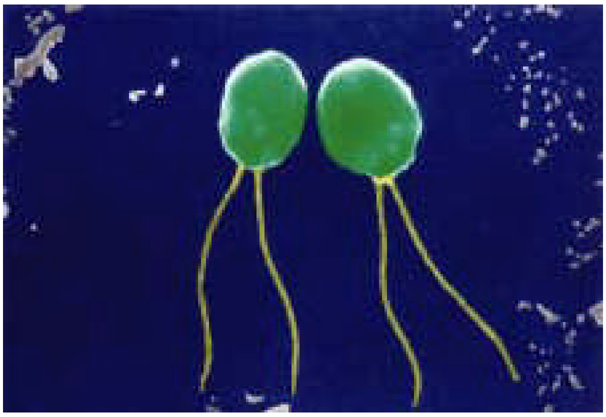
(www.**eere.energy.gov**/biomass/pdfs/biodiesel_from_algae.pdf)

National Renewable Energy Laboratory

NREL/TP-580-24190

A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae





Close-Out Report

A Look Back at the U.S. Department of Energy's Aquatic Species Program—Biodiesel from Algae

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By

John Sheehan
Terri Dunahay
John Benemann
Paul Roessler

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Prepared by: the
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
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Executive Summary

From 1978 to 1996, the U.S. Department of Energy's Office of Fuels Development funded a program to develop renewable transportation fuels from algae. The main focus of the program, know as the Aquatic Species Program (or ASP) was the production of biodiesel from high lipid-content algae grown in ponds, utilizing waste CO_2 from coal fired power plants. Over the almost two decades of this program, tremendous advances were made in the science of manipulating the metabolism of algae and the engineering of microalgae algae production systems. Technical highlights of the program are summarized below:

Applied Biology

A unique collection of oil-producing microalgae.

The ASP studied a fairly specific aspect of algae—their ability to produce natural oils. Researchers not only concerned themselves with finding algae that produced a lot of oil, but also with algae that grow under severe conditions—extremes of temperature, pH and salinity. At the outset of the program, no collections existed that either emphasized or characterized algae in terms of these constraints. Early on, researchers set out to build such a collection. Algae were collected from sites in the west, the northwest and the southeastern regions of the continental U.S., as well as Hawaii. At its peak, the collection contained over 3,000 strains of organisms. After screening, isolation and characterization efforts, the collection was eventually winnowed down to around 300 species, mostly green algae and diatoms. The collection, now housed at the University of Hawaii, is still available to researchers. This collection is an untapped resource, both in terms of the unique organisms available and the mostly untapped genetic resource they represent. It is our sincere hope that future researchers will make use of the collection not only as a source of new products for energy production, but for many as yet undiscovered new products and genes for industry and medicine.

Shedding light on the physiology and biochemistry of algae.

Prior to this program, little work had been done to improve oil production in algal organisms. Much of the program's research focused attention on the elusive "lipid trigger." (Lipids are another generic name for TAGs, the primary storage form of natural oils.) This "trigger" refers to the observation that, under environmental stress, many microalgae appeared to flip a switch to turn on production of TAGs. Nutrient deficiency was the major factor studied. Our work with nitrogen-deficiency in algae and silicon deficiency in diatoms did not turn up any overwhelming evidence in support of this trigger theory. The common thread among the studies showing increased oil production under stress seems to be the observed cessation of cell division. While the rate of production of all cell components is lower under nutrient starvation, oil production seems to remain higher, leading to an accumulation of oil in the cells. The increased oil content of the algae does not to lead to increased overall productivity of oil. In fact, overall rates of oil production are lower during periods of nutrient deficiency. Higher levels of oil in the cells are more than offset by lower rates of cell growth.

Breakthroughs in molecular biology and genetic engineering.

Plant biotechnology is a field that is only now coming into its own. Within the field of plant biotechnology, algae research is one of the least trodden territories. The slower rate of advance in this field makes each step forward in our research all the more remarkable. Our work on the molecular biology and genetics of algae is thus marked with significant scientific discoveries. The program was the first to isolate the enzyme Acetyl CoA Carboxylase (ACCase) from a diatom. This enzyme was found to catalyze a key metabolic step in the synthesis of oils in algae. The gene that encodes for the production of ACCase was eventually isolated and cloned. This was the *first* report of the cloning of the full sequence of the ACCase gene in *any* photosynthetic organism. With this gene in hand, researchers went on to develop the first successful transformation system for diatoms—the tools and genetic components for expressing a foreign gene. The ACCase gene and the transformation system for diatoms have both been patented. In the closing days of the program, researchers initiated the first experiments in metabolic engineering as a means of increasing oil production. Researchers demonstrated an ability to make algae over-express the ACCase gene, a major milestone for the research, with the hope that increasing the level of ACCase activity in the cells would lead to higher oil production. These early experiments did not, however, demonstrate increased oil production in the cells.

Algae Production Systems

Demonstration of Open Pond Systems for Mass Production of Microalgae.

Over the course of the program, efforts were made to establish the feasibility of large-scale algae production in open ponds. In studies conducted in California, Hawaii and New Mexico, the ASP proved the concept of long term, reliable production of algae. California and Hawaii served as early test bed sites. Based on results from six years of tests run in parallel in California and Hawaii, 1,000 m^2 pond systems were built and tested in Roswell, New Mexico. The Roswell, New Mexico tests proved that outdoor ponds could be run with extremely high efficiency of CO_2 utilization. Careful control of pH and other physical conditions for introducing CO_2 into the ponds allowed greater than 90% utilization of injected CO_2. The Roswell test site successfully completed a full year of operation with reasonable control of the algal species grown. Single day productivities reported over the course of one year were as high as 50 grams of algae per square meter per day, a long-term target for the program. Attempts to achieve consistently high productivities were hampered by low temperature conditions encountered at the site. The desert conditions of New Mexico provided ample sunlight, but temperatures regularly reached low levels (especially at night). If such locations are to be used in the future, some form of temperature control with enclosure of the ponds may well be required.

The high cost of algae production remains an obstacle.

The cost analyses for large-scale microalgae production evolved from rather superficial analyses in the 1970s to the much more detailed and sophisticated studies conducted during the 1980s. A major conclusion from these analyses is that there is little prospect for any alternatives to the open pond designs, given the low cost requirements associated with fuel production. The factors that most influence cost are biological, and not engineering-related. These analyses point to the need for highly productive organisms capable of near-theoretical levels of conversion of sunlight to biomass. Even with aggressive assumptions about biological productivity, we project costs for biodiesel which are two times higher than current petroleum diesel fuel costs.

Resource Availability

Land, water and CO_2 resources can support substantial biodiesel production and CO2 savings.

The ASP regularly revisited the question of available resources for producing biodiesel from microalgae. This is not a trivial effort. Such resource assessments require a combined evaluation of appropriate climate, land and resource availability. These analyses indicate that significant potential land, water and CO_2 resources exist to support this technology. Algal biodiesel could easily supply several "quads" of biodiesel—substantially more than existing oilseed crops could provide. Microalgae systems use far less water than traditional oilseed crops. Land is hardly a limitation. Two hundred thousand hectares (less than 0.1% of climatically suitable land areas in the U.S.) could produce one quad of fuel. Thus, though the technology faces many R&D hurdles before it can be practicable, it is clear that resource limitations are not an argument against the technology.

Experiments were also carried out in the small pond, primarily to determine the best operating pH and pCO_2 range to help minimize CO_2 outgassing while maximizing productivity. At reduced CO_2 levels (higher pH) a decrease of 10% to 15% in productivity was observed with three algal species tested. Another variable tested was a 2- versus 3-day dilution routine, which had no significant effect. In addition, six cultures were examined for productivity in Si- or N-deficient media. Only one strain exhibited significantly higher total (AFDW) productivities with nutrient deficiency, but no lipid data were collected.

The conclusions from this work were, in brief:

1. Power for pond mixing is within the expected range, and quite low (<1 kW/ha).

2. Pond mixing should be in the 15-25 cm/s range, and pond depth 15-25 cm.

3. CO_2 utilization efficiencies of near 90% overall should be achievable with little compromise of productivity, through operation at an optimal pH/pCO_2 range.

4. Only preliminary 1,000-m^2 pond operations were carried out during this year, hampered by design and operational problems, which lowered expected productivities.

5. Large-scale pond productivities of 70 mt/ha/yr are realistic goals for this process, though probably not at this site because of low seasonal productivities.

6. Very high, 50 $g/m^2/d$, single day, productivities were observed on some occasions.

7. The small-scale ponds can be used to screen strains and optimize conditions.

The final report (Weissman and Tillett 1992) in this series on the New Mexico OTF operations, reported on the demonstration of productivity for the two large ponds for 1 full year, continuation of the small-scale pond operations, and improvements in mixing and carbonation. One major improvement in the system was an automated data recording and operations system.

Mixing was improved by improving the flow deflectors and increasing operating depths from 15 to 22.5 cm, which is probably a better depth for large-scale systems. Culture instability was a problem, particularly in spring because of greater temperature fluctuations, and resulted in low average productivity of only 7 $g/m^2/d$ for March through May. In contrast, the average productivity was 18 $g/m^2/d$ for June through October, decreasing to 5-10 $g/m^2/d$ in November (depending on onset of cold weather), and only about 3 $g/m^2/d$ in the winter months.

Overall productivity, including 10%-15% down-time for the ponds for repairs and modifications, was 10 $g/m^2/d$, only one-third of ASP goals (Table III.B.3.). Clearly the major limiting factor was temperature, as smaller systems in warm climates have achieved annual yields two to three times as high. A major conclusion from this work is that scale-up is not a limitation with such systems. Climatic factors are the primary ones that must be considered in their siting.

A countercurrent flow injection system was installed in the sumps resulting in a carbonation system that was essentially 100% efficient in CO_2 transfer. Overall CO_2 utilization was higher than 90%. The unlined pond performed nearly as well as the lined pond, with minor decreases in productivity (10%-20%), CO_2 utilization efficiency (5%-10%) and a small increase in mixing power. The unlined pond consumed only 0.04 w/m^2, allowing the entire 1,000-m^{2}pond to be powered by the equivalent of a 40-w light bulb. Species stability in the lined and unlined pond exhibited no significant difference. This work clearly established the feasibility of using unlined ponds in microalgae cultivation. This was a critical issue, as plastic lining of ponds is not economically feasible for low-cost production.

In the small 3-m^2 systems, two variables were investigated: Si supply and pH. Both are major cost factors in pond operation, due to sodium silicate costs and CO_2 outgassing. They affect overall productivity as well as lipid production. For *Cyclotella,* for example, productivity was about 20 g/m^2/d at pH 7.2 or 8.3, but only 15 g/m^2/d at pH 6.2. As the higher pH range is preferred, where CO_2 outgassing is minimal, this demonstrates the feasibility of operating such cultures within the constraints of a large-scale production system. Si additions could be halved with only a modest decrease in productivity, suggesting that Si supply could be reduced, particularly if low Si-containing diatoms are cultivated. Also Si limitation can be used to induce lipid production, as was demonstrated during this project, with lipid biosynthesis increasing as soon as intracellular Si content dropped, with a 40% lipid content being achieved. However, overall, lipid productivity did not increase as CO_2 fixation limitation also set in. This remains as a major issue for the future (See also Section III.B.5.d.).

Table III.B.3. Long Term OTF Results from 0.1-Ha Raceways.

(Source: Weissman and Tillett 1990.)

Pond Liner	CO_2 use (std.m3/d)	Dates	Productivity (gm afdw/m2/d)	Carbon Use Efficiency	Water Loss
YES	15.2	10/1/88-9/30/89	9.8	59	5.7 mm/d
NO	13.4	10/1/88-9/30/89	8.3	50	6.2 mm/d
NO	14.6	10/1/89-9/30/90	10.5	82	
YES	22.0	6/1/90-10/30/90	19	81	
NO	19.2	5/1/90-9/30/90	18	88	

Notes: std m^3/d: standard cubic meters per day.

gm/afdw/m^2/d: grams of ash-free dry mass per square meter per day.

Pond liner: **YES** indicates a plastic lined pond; **NO** indicates an unlined (dirt bottom) pond.

III.B.5.d. *Conclusions*

The performance of the large-scale system improved considerably in all aspects during the 2 years of operations. The parallel use of the smaller-scale ponds helped guide this research, in particular in selecting algal strains and identifying operating characteristics. The high CO_2 utilization efficiency demonstrated in the small and large-scale ponds was another major accomplishment of this project.

The major limitation of this project was the overall low productivity in the large-scale ponds. This was due in large part to the adverse climatic conditions at this location, and the initial suboptimal nature of the large-scale pond operations. Even so, productivities were lower than anticipated, with annual average productivities only about one-third the projected productivities by the ASP that would be required for minimal economics (see Section III.D.). This must be a major ongoing objective for future research, first in terms of overcoming the lower temperature limitations on productivity, and second by relocating this type of process development to more favorable climatic sites. (See Section III.B.6. for a discussion of temperature effects.)

But perhaps the major limitation of this project was that it did not carry out a longer-term process development effort. Although 2 years of data were collected for the large-scale ponds, the rapid advances made suggested that further research would have allowed continued improvements in performance and increased understanding of the overall process in specific critical areas of culture maintenance.

The engineering evaluation of the operation of the 0.1-ha raceway ponds showed these systems to be potentially very efficient in terms of energy, water, nutrient and CO_2 utilization, and even basic construction cost inputs. Most important, the absence of liners did not significantly reduce pond performance (e.g., productivity). This was a major observation of this project, giving greater confidence in the engineering analysis and cost projections carried out by the ASP and DOE, discussed again in Section III.C.

A major uncertainty in this project was the nature of the species control achieved. A review of the data would suggest considerable success with species control, with several species cultivated successfully for relatively long periods. However, considerably more research will be required on this subject, as the tools were not available to allow a closer study of possible population dynamics (e.g., strain selection and even replacement) within the ponds. Thus, the subject of species control still requires considerable effort, as discussed further in the following section.

Publications:

Weissman, J.C.; Goebel, R.P. (1987) "Design and analysis of pond systems for the purpose of producing fuels." *Report to the Solar Energy Research Institute*, Golden, Colorado, SERI/STR-231-2840.

III.C.5. The 1990 SERI Study on CO_2 Sources

The objective of this study (Feinberg and Karpurk 1990) was to examine CO_2 resources for microalgae production in the year 2010 and beyond. This report was a very comprehensive and authoritative source of information on this subject, from merchant CO_2 supplies and costs to potential competition from EOR for CO_2 sources. CO_2 recovery from existing processes was judged to be relatively low cost from ethanol and ammonia plants, and much more expensive from cement, refineries, or power plants.

After a detailed review of the options, the authors estimated that the potential CO_2 resource base was sufficient to support the annual production of roughly 2 to 7 quads of algal fuels. This corresponds to as much as 1.1 billion tons of CO_2 per year, at prices ranging from about \$9 to \$90/t CO_2. However, this analysis lacks the spatial resolution of the earlier study; thus, the actual CO_2 availability (particularly of the low-cost supplies) was somewhat more speculative. Certainly CO_2 resources will be a major limiting factor in microalgae production technology. However, as CO_2 utilization has become a central objective of microalgae production systems, perhaps rather than looking at CO_2 as a limitation it should be considered a site-specific opportunity, where the other requirements for microalgae production are met (e.g., land, climate, water, infrastructure). Table III.C.1. summarizes the conclusions of this report regarding CO_2 costs and supplies.

Publications:

Feinberg, D.A.; Karpuk, M.E. (1990) "CO_2 sources for microalgae based liquid fuel production." *Report,* Solar Energy Research Institute, Golden, Colorado, SERI /TP-232-3820.

Karpuk, M. (1987) "CO_2 sources for fuels synthesis." *FY 1986 Aquatic Species Program Annual Report*, Solar Energy Research Institute, Golden, Colorado, SERI/SP-231-3071, pp. 269-275.

Table III.C.1. Summary of Availability and Cost of CO_2 Sources

(Source: Feinberg and Karpuk, 1990.)

CO_2 Source	Potential (10^6 kg/y)	Estimated Cost ($1986/mt)
Concentrated, high pressure sources:		
Liquid synthetic fuel plants	40	12 - 16
Gaseous synthetic fuel plants	220	
Gasification/combined cycle power plants	0-790	9-16
Concentrated low-pressure sources:		
Enhanced oil recovery	8-32	
Ammonia plants	9	9-16
Ethanol plants	<0.1	
Dilute high pressure sources:		
Non commercial natural gas	52-100	11-53
Refineries	13	54-95
Dilute low pressure sources:		
Anaerobic digestion (biomass/wastes)	230	11-84
Cement plants	26	51-84
Fossil steam plants	0-790	29-48
TOTALS	600 - 2250	

III.C.7. Conclusions

The various ASP resources analyses indicated significant potential land, water, and CO_2 resources, even within the limited geographic area (the southwestern United States) that was the focus of the ASP. Several quads (10^{15} Btu) of fuels were projected for the various available resources. Other areas, from Florida to California, could also be considered. Microalgae systems actually use fairly little water, compared to irrigated crop plants. In addition, many waste and saline water resources may be available and suitable for microalgae production. Many CO_2 sources are available, and algal ponds could be purposefully co-located with CO_2 sources, or even vice versa. This is already being done at a commercial microalgae facility in Hawaii. Finally, land is hardly a major limitation: two hundred thousand hectares, less than 0.1% of climatically suitable land areas in the United States, could, with maximal productivities, produce about 1 quad of fuels. Thus, although there are many practical limitations, which may make some earlier predictions optimistic, resource limitations should not be an argument against microalgae biodiesel systems.

III.D. Engineering Systems and Cost Analyses

III.D.1. Introduction

One of the major accomplishments of the ASP was the development of detailed engineering/cost projections for large-scale microalgae biofuels production. These analyses generally supported the view that microalgae biomass production could be performed at sufficiently low cost as to plausibly become a renewable energy source, assuming however, that the rather ambitious R&D goals of the ASP could be met. A major conclusion from reviewing these studies is that most R&D goals for this technology are related to the algal cultures themselves (productivity, species control, and harvestability), rather than the engineering aspects, such as the ponds, CO_2 transfer, or biomass processing.

Historically, the first engineering and cost analysis for large-scale microalgae production of fuels was that of Oswald and Golueke (1960). These authors projected the costs of electricity generated from biogas (methane) obtained from the anaerobic fermentation of algal biomass. The algae were to be cultivated in very large (40-ha) raceway type ponds, mixed with pumps, and supplied with CO_2 from a power plant. Other nutrients would come from the digesters. Municipal wastewaters would be used as make up for water and nutrients (C, N, P, etc.). The ponds were to be of earthen construction, with a depth of about 30-cm. Harvesting was assumed to be by simple settling. Electricity costs were projected to be competitive with nuclear power. Although few details were provided, the general concept outlined in this early publication has remained essentially unchanged. Perhaps the greatest change is that biomass productivities thought to be achievable at that time were less than 50 mt/ha/yr of biomass, while current projections are roughly two to five times higher.

With the initiation of the ERDA/DOE funded projects at the University of California–Berkeley during the mid-1970s (Section III.A.), additional engineering and cost analyses were conducted

(Benemann et al. 1977). The early studies were based on large (8–20-ha) ponds, with multiple channels and mixing by recirculation pumps (the required deep concrete sumps and splash pads were a major cost factor). Both the settling pond for harvesting algae by sedimentation and a covered anaerobic lagoon were part of this initial design. Total systems costs were only about $10,000/ha (somewhat over twice that in current dollars). Based on a projected yield of about 500 GJ/ha/y (10 GJ/t of algal biomass) of biogas, costs were projected at about $3/GJ. Although optimistic, this study served as a starting point for more detailed later studies.

Publications:

Oswald, W.J.; Golueke, C.G. (1960) "Biological transformation of solar energy." *Adv. Appl. Microbiol*. 11:223-242.

Benemann, J.R.; Baker, D.; Koopman, B.L.; Oswald, W.J. (1977) "A systems analysis of bioconversion with microalgae." *Proc. Symposium Clean Fuels from Biomass and Wastes,* (Klass, D., ed.) Institute of Gas Technology, Chicago, pp. 101-126.

III.D.2. The Algal Pond Subsystem of the "Photosynthesis Energy Factory"

A relatively detailed analysis of an algal wastewater treatment-energy production process was carried out by Benemann et al. (1977) as part of a larger study that examined a system integrating wastewater algal ponds with tree biomass production. The so-called "Photosynthetic Energy Factory" (InterTechnology Solar Corporation 1978) was to use the effluents of a waste treatment pond system to fertilize short-rotation trees for fuel farming. In turn, the power plant burning the woody biomass would provide CO_2 for the algal ponds.

A design of the algal pond subsystem was carried out by Benemann et al. (1978) for a typical municipal community of 50,000 people, generating approximately 18,000 m^3 of municipal wastewater per day. The assumption was that algal biomass would be grown up to the N growth potential of the wastewater, containing 65 mg/L of useable N (as organic N and ammonia). This required recycling about 5 to 7 tons of CO_2 per day from the power plant to the algal ponds. A temperate site with an average insolation of about 15 $GJ/m^2/d$ was assumed, with a solar conversion efficiency averaging only 2.7% of visible light (about 1.35% of total solar), somewhat higher in winter than summer. This is considerably lower than current assumptions.

This study, for the first time, took into consideration monthly variations in temperature, insolation and other parameters. Algal harvesting was assumed to be with microstrainers (this analysis was carried out while this option was still being investigated, see Section III.A.3.). This report also carried out the first, though preliminary, analysis of the mixing power required for such large algal ponds and of the transfer requirements for CO_2 to the algal culture. A 160-ha algal pond system was required to treat this wastewater flow year-round. This was about three times larger than a conventional oxidation pond system. Costs were projected to be competitive with conventional wastewater treatment systems.

Energy outputs were twice the energy inputs, based on digester gas production and requirements for pumping the wastewater, mixing the ponds, etc. The overall economics were very favorable because of the wastewater treatment credits.

Although this concept appeared favorable, in practice the relatively small scale of the locally available municipal wastes could supply only a small fraction of fertilizer needs for the very large (>10,000 ha) energy plantations being projected. It does, however, point to the potential of this technology in wastewater treatment.

Publications:

Benemann, J.R.; Koopman, B.L.; Baker, D.; Goebel, R.; Oswald, W.J. (1977) "Preliminary design of the algae pond subsystem of the photosynthesis energy factory." *Final Report to Inter-Technology Solar Corp.*, Sanitary Eng. Res. Lab., Univ. of Calif.-Berkeley.

InterTechnology/Solar Corp. (1978) "The photosynthesis energy factory: analysis, synthesis and demonstration." U.S. DOE HCP/T3548-01.

III.D.3. Cost Analysis of Microalgae Biomass Systems

This report (Benemann et al. 1978) originated with a Request for Proposals (RFP) by ERDA for a "Cost Analysis of Algal Biomass Systems" which included both micro- and macroalgae. The contract was awarded to the Dyantech R/D Co., who subcontracted for the analysis of the microalgal work with CSO International, Inc. Although the RFP specified a minimum scale for such systems of "100 square miles," a single large unit was not feasible, and the analysis was carried out for individual modules of 800-ha. This system was to be independent of wastewater treatment and nutrients, which were deemed too small to provide "meaningful" energy supplies.

The first step in the analysis was to list 10 major sets of assumptions on which this process could be based (Table III.D.1.). These included

- essentially effortless species control,
- a yield of about 45 mt/ha/yr (20 t/ac/y),
- 4% N and 0.4% P in the algal biomass,
- 40 ha (100 ac) growth ponds with multiple channels, and
- harvesting by bioflocculation.

Month-by-month variations in biomass density, productivity, water and CO_2 utilization, etc. were estimated based on a typical southwestern United States location, with productivities ranging from a minimum of 6 to a maximum of 18 $g/m^2/d$.

Based on these assumptions, designs of the various system components were carried out, and supporting calculations made for the subsystems, including earthworks, pumps to move and lift the water, the supply channels and piping required, transfer structures, settling ponds, ducting for CO_2, etc. The algal biomass would be digested to methane gas, but this was not included in the analysis. Based on estimates for various components, total capital costs were estimated (in 1978 dollars) at about $9,000/ha, without contingencies or engineering. Annualized costs, based on a 15% per annum capital charge, plus $700/ha operating costs for labor and nutrients, assuming free CO_2, were about $2,000/ha, or about $45/t biomass. As pointed out in the report, “the basis for choosing many of the design features was low cost, or, actually, the highest cost allowable.” Thus, this report was primarily useful in identifying the major design assumptions and cost centers for such a process.

This report was the first truly detailed analysis of such systems, though it still was, in many aspects, highly conceptual. It was used by Regan (1980) for a similar analysis of a large-scale algal (*B. braunii*) hydrocarbon production process in Australia, and served as the basis for subsequent analysis by DOE and the ASP.

Publications:

Benemann, J.R.; Persoff, P.; Oswald, W.J. (1978) “Cost analysis of microalgae biomass systems.” *Final Report prepared for the U.S. Dept. of Energy*, HCP/t1-605-01 Under Contract EX-78-X-01-1 605.

Regan, D.L. (1980) “Marine biotechnology and the use of arid zones.” *Search* 111:377-381.