Microalgae Production Cost Analysis

Development of Goals

And Its Implications On Future Research

SERI
Biomass Program Office

January 17, 1984

Prepared by:
Andrew M. Hill and Robins P. McIntosh

Table of Contents

List of Tables

List of Figures

1.0 Introduction

This paper presents an overview of the production and economic models, with specific discussion of input assumptions used to derive microalgae product costs for the state of the art, theoretical-best and for the 1994 attainability target. These product cost estimates form the basis for developing program cost goals for microalgae fuel technology.

The purposes of this paper are severalfold. The first objective is to establish an estimate of product costs for a microalgae-for-fuel production facility based upon input values representative of the current state of the art for the technology. Secondly, establish a unit production cost that represents an absolute best achievable based upon the known physical limits of photosynthetic organisms. A comparison of the current state of the art production cost with the theoretical best production cost bounds the limits of what is currently achievable and ultimately attainable and provides an indication of the extent to which research improvements in microalgae production can reduce product costs. A third objective is to conduct sensitivity analyses of several input assumptions used to estimate state of the art costs. Parametric analyses to determine the input assumptions with the greatest influence on unit production costs will aid in establishing research areas in which improvements can reduce unit costs. A fourth and final objective is to establish one set of input assumptions that are believed attainable by 1994. These assumptions represent the considered judgment of researchers as to the performance levels that might be attained through continued research efforts.

Production costs for microalgae derived fuel products are estimated by a biological production and an economic revenue-required model developed at SERI under the subtask entitled, "Cost Analysis for Microalgae Production."

2.0 Overview of Microalgal Analysis Model

2.1 Production Model

The production model estimates gross biomass yields for a facility of a given size. The equation which follows was reported by Oswald and Benemann in "Biochemical and Photosynthetic Aspects of Energy Production," edited by Anthony San Pietro (1980). Providing the basis for estimating gross yields of algal biomass, the equation is most appropriate for steady-state continuous flow culture systems similar to chemostats. The input parameters of depth, detention time (or the inverse of dilution rate) and culture density are based on empirical data obtained from field experiments.

$$\text{Production} = \left(\frac{D}{\Theta}\right) d \, C_f \, Z \, (.01)$$

Where:

Production = Gross yield (dry ash-free metric tons per year)
D = Culture depth (meters)
Θ = Retention time (days)
C_f = Capacity factor (days per year)
Z = Facility size (hectares)
d = Culture density (mg/l)
.01 = Scaling constant

Photosynthetic efficiency is calculated from the gross biomass yield using average daily solar insolation representative of the Southwest United States (5000 $\text{Kcal/m}^2\text{/d}$) and the average total energy content of the algal biomass, (Kcal per gram) determined from user-defined input assumptions for gross lipid and carbohydrate content (heating value for lipid, carbohydrate and protein fractions are 9.3 Kcal/g; 3.7 Kcal/gm and 5.6 Kcal/gm respectively; Milner; in Bulew, 1976). The ash content of the algae is fixed at 8% of dry cell weight.

$$\text{Photosynthetic Efficiency} = \frac{\text{total annual energy output}}{\text{total annual energy input}}$$

Where:

Total annual energy output = total algal yield x average heating content of algal biomass (Kcal/yr)

Total annual energy input = average daily solar radiation x fraction of total light spectrum available for photosynthesis x capacity factor x facility size (Kcal/yr).

Net biomass yield for the facility is calculated by multiplying production by user defined harvesting efficiency.

Lipid production is calculated from net biomass yield and lipid content (% of ash free dry weight), the latter parameter being user defined. The conversion of product tons to product barrels assumes 146.7 kilograms per barrel (Lipinsky, et. al. 1981).

2.2 Capital Costs

Capital costs were derived from Benemann (1982) in which the author updated 12 previously published economic analyses of microalgae production and developed product costs. Because of inconsistency among the studies in facility size, type of harvesting system, land costs and indirect capital investment requirements (e.g., engineering fees and contingencies), SERI used only those costs associated with growth pond construction, pumps, piping and other fixed onsites (e.g, buildings, fences, etc.) to develop a relationship between facility size (acres) and pond construction costs ($ per acre). This relationship is presented in Figure 1.0 as a line entitled "Pond Construction Only." The correlation coefficient for the least squares regression line is .77, indicating a reasonable fit of the data.

Figure 1.0 suggests declining unit costs with increased facility size. The extent to which this relationship indicates real economies of scale is not certain in the absence of actual cost histories of large scale microalgal systems. It is expected that a large scale facility would be comprised of a number of individual modules linked together through nutrient, water and harvesting distribution subsystems. Whether declining unit costs for large scale systems are applicable to a single module or to the entire facility is uncertain; however, economics of scale have been noted in analogous systems such as EPA waste treatment systems and desalination ponds. The results presented in this paper are based on developing capital costs as a function of total facility size.

Total capital investment is estimated by including engineering fees, contingency, land costs and a harvesting subsystem defined by the user. Engineering fees are estimated at 22% of the capital investment for the culture system and harvesting system. Contingencies are estimated at 10% of the capital investment plus engineering fees. Land costs are user defined according to an assumed unit price ($ per hectare) and facility size.

Currently, the SERI model is capable of analyzing three harvesting subsystems; microstrainer, nozzle centrifuge and settling ponds. Capital costs for each system are normalized to a 35,000 gallon per hour harvesting system with a size-cost exponent of .796 (Intertechnology, 1978). Thus, the model calculates flow rate (culture volume/retention time) to the harvesting subsystem and sizes the harvester accordingly.

2.3 Operating Costs

Operating costs for the microalgae production facility include direct labor, overhead, maintenance expenses, utility costs and nutrient expenses.

Direct labor is assumed to involve five men per 100 hectares having an annual salary of $20,000. Overhead costs are 75% of the direct labor expenses. Maintenance expenses are assumed to be 2% of the capital investment for the growth ponds and harvesting subsystem.

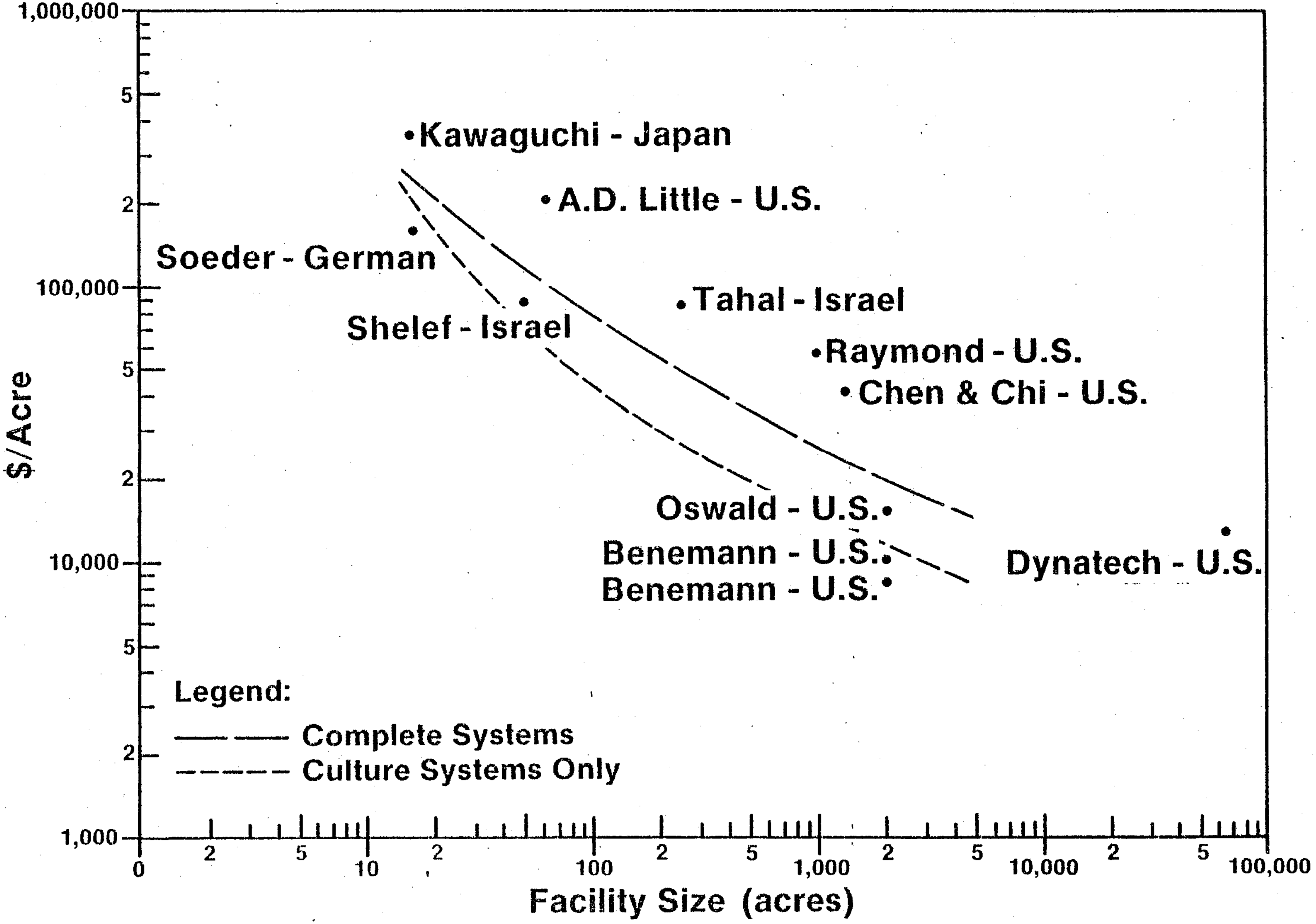
Utility expenses include the costs associated with operation of the harvester subsystem, mixing subsystem and pumping requirements (e.g., make-up, harvester, and recycle). The flowrate (gallons per hour) in each pumping subsystem determines the required power demand. Harvester total energy requirements are estimated according to unit energy use estimates (kWh per m^3) as reported by Mohn (1980) multiplied by the throughput of the harvesting subsystem. Mixing velocity energy requirements are estimated by calculating headloss through the culture system according to Benemann (1982). The model allows the user to define a geometric shape of the culture system (length, width and depth) in order to calculate appropriate headloss. The computer model calculates the horsepower requirements necessary to overcome channel headlosses and maintain a user defined mixing velocity in the culture channel. Using assumptions for capacity factor of the facility, total kilowatthours required for the pumping subsystem, harvester subsystem and mixing subsystem are calculated and used to determine total energy costs according to user specified unit energy costs ($ per kilowatthour).

Figure 1.0

Relationship Between Capital Cost and Facility Size for Microalgae Systems

Dollars per Acre (1982$)

(Hill, 1982)



Nutrient expenses are derived from the gross production yield estimates based upon general elemental composition of microalgae. For example, if 50% of algae is carbon, then .5 metric tons of carbon are required per metric ton of algae gross yield. The amount of carbon dioxide (CO_2) as a carbon nutrient source, required to sustain a metric ton of algae is determined by the ratio of the molecular weight of carbon dioxide (44) to the atomic weight of carbon (12). Thus, one metric ton of algae would require 1.7 metric tons of CO_2. Nutrient expense for nitrogen, potassium and phosphorus are similarly determined according to this adjusted nutrient requirement multiplied by a nutrient supply price selected by the user. The major nutrients are supplied as indicated in Table 1.0. The nutrient prices are based upon supplier quotes for spot purchases as listed in the Chemical Marketing Reporter, and do not reflect contracted prices that might be available to large users of industrial chemicals. Contract prices for chemicals for use in microalgae production can be significantly lower than the spot prices presented in Table 1.0. A sensitivity analysis of the effect of spot versus contract prices on lipid oil costs is included in Table 5.0, Section 6.1.

Table 1.0-Major Nutrients Supplied To Microalgae Culture Facility and Related Supply Costs.

Nutrient	Supplied as	Market Price ($/metric ton)	(Refs)
Carbon	Carbon dioxide	$82.5	(1)
Nitrogen	Ammonia	$203.0	(2)
Potassium	Potassium Muriate	$102.0	(2)
Phosphorus	Superphosphate	$281.6	(2)

Notes:
(1) Argonne, (1983) estimate of current commercial CO_2 price.

(2) Chemical Marketing Reporter (Sept. 12, 1983).

2.5 Revenues-Required Economic Model

Once the system specific operational parameters are calculated, the model determines the finances of the microalgal facility by utilizing a capital budgeting technique. Doane, et. al. (1978) reported a required revenue methodology for providing comparative evaluation of technologies using standard and consistant economic and financial parameters. The economic model determines the present value of capital investment costs (including interest during construction) and the present value of annually recurring costs over the system lifetime. This aggregated present value is distributed over the system lifetime in equal cash flows for each annual time period and then divided by the expected yearly energy output. The result is a required unit price for the energy product, the revenues of which would exactly recover the full costs of the system over its lifetime, including a return on the investments of stockholders and creditors. This methodology specifies a unit product cost in constant dollars necessary for the net present value of revenues and costs for a production facility to equal zero. The weighted average after tax cost of capital internally computed by the economic model represents the internal rate of return for the facility.

3.0 Input Assumptions used to Calculate Production Costs

To calculate production costs for a microalgae facility, operational and financial parameters must be specified. The financial assumptions used to develop state-of-the-art and theoretical cost estimates for microalgae production are listed in Appendix A.

To facilitate comparison between different sets of operational data, consistent supply cost and financial parameters are maintained. Where difference values between SOTA and theoretical parameters occur, the changes reflex a degree of optimistism appropriate with the definition of theoretical best. Carbon costs and real escalation in capital and operating costs are lowered in the theoretical best case. Recycling is increased and the time frame for construction varies. The SOTA case presumes near-term application of currently available technology; whereas the theoretical best case presumes a long term improvement in biological and engineering parameters.

System specific parameters are presented in Table 2.0 for the SOTA and theoretical best design facilities. Since photosynthetic efficiency determines annual yield, the theoretical best values presented in Table 2.0 result from an assumed PAR efficiency of 24%. Yield, calculated from values for depth, detention time and density, was determined by increasing culture density while holding constant values for detention time and culture depth.

Table 2.0 Operational Input Parameters Used to
Calculate Microalgal Production Costs

	SOTA	Theoretical
Density (mg/L)	800	2200
Retention time (days)	5	5
Depth (cm)	15.2	15.2
Mixing Velocity (m/sec)	.305	.305
Mixing System	Paddlewheel	
Efficiency (%)	56.0	67.5
Harvesting System	Settling Pond	
Efficiency (%)	95	100
Lipid Content (% dry ash-free weight)	30	70
Carbohydrate Content (% dry ash-free weight)	15	10
Non Carbon Nutrient Recycle	0	90

4.0 State of the Art Technology Costs

This section presents microalgal product costs. These costs (expressed in 1983 dollars) represent the revenue-required price allowing a specified return on investment over the lifetime of the facility. The cost estimates are based on a commitment to build a 405 hectare (1000 acre) facility in 1983 to be operational in 1985.

The microalgae production system is estimated to be capable of producing 134.7 barrels of lipid oils per hectare per year. This product yield is based on a total net biomass yield of 66.0 metric tons per hectare per year (gross productivity of 23.0 g/m^2-d). Overall photosynthetic efficiency for the system is 5.9% of the photosynthetically active region (PAR) based on insolation values representative of the U.S. southwest. Processing losses were assumed at 5% of gross yield.

Construction costs for the growth ponds, pipes, pumps, buildings, and offsites are estimated to be $37,600/hectare (in 1983 dollars), or $3.76/$m^2$. Including a harvesting system, the total depreciable capital investment is approximately $55,330 per hectare. Additional capital cost charges for engineering, contingencies, and land increase result in total fixed costs for the microalgae production facility to $75,560 per hectare. On an annualized cost basis, these fixed costs ($5,150 per hectare) represent 18.8% of the total product costs for microalgae production as indicated in Table 4.0

Variable costs or costs associated with annual operation of the microalgae facility represent 81.2% of the total annualized costs and are directly proportional to production output. The major variable cost category is nutrient requirements to sustain the biomass production (54.5% of the total variable costs). Utilities requirements to run the pumping subsystems (e.g., recirculation) constitute the second largest cost category. Power for mixing — the amount of horsepower required to maintain a specific flow velocity along the channel length — requires the most energy. Of the total utility energy demand (22.9 x 10^6 kWh), 69.4% is required to maintain a 30.5 cm/s velocity. The settling pond harvesting system consumes 3.5 x 10^6 kWh (15.3 of the total utility energy requirements of the facility) with the balance attributed to recirculation requirements. The total annualized variable costs for the system are $8.9 million or $336.5 per net metric ton of biomass. The levelized product cost for microalgae lipids from this state-of-the-art facility is $203 per barrel of oil, based upon an average lipid content of 30%.

Table 3.0 Summary of Microalgae Production Costs
for the State of the Art Design Systems.

	$/per Barrel	% of Total
Annualized Capital Investment	38.2	18.8
Annual Operating Cost		
Utilities	27.4	13.5
Nutrients	110.8	54.5
O & M	10.1	4.9
Labor and Overhead	16.5	8.1
Total Production Cost ($/BBL)	203.1	100.0

5.0 Theoretical Cost Estimates

Certain input parameters have potential for improvements through continued research efforts. To define the absolute "best" operational conditions for the pond and raceway systems, specific engineering and biological parameters were set at their maximum possible values, thus bounding the limits of attainability. These limits for biological and engineering parameters are presented in Tables 2.0 and Appendix A.

For the theoretical best production facility net production yield of biomass is 232 metric tons per hectare-year resulting from a productivity of 63.7 grams per square meter-day. Lipid product yield is 1100 barrels per hectare-year and it is assumed that there are no harvesting losses.

Table 4.0 summarizes the distribution of annual costs for the theoretical best production. Compared with the SOTA cost summary presented in Table 3.0, the distribution of annual costs between the two cases is similar. Recycling of non carbon nutrients and a lower delivered price for carbon dioxide reduce the nutrient supply costs to 42.6% of the total costs. Annualized capital costs as a percentage of total product costs increase slightly from the SOTA estimate since no improvements in unit capital costs for the theoretical best facility were assumed, and other costs are reduced.

Table 4.0 Summary of Microalgae Production Costs
for the Theoretical Best Design System

	$/per Barrel	% of Total
Annualized Capital Investment	4.5	26.6
Annual Operating Cost		
Utilities	2.7	15.9
Nutrients	7.2	42.6
O&M	.9	5.3
Labor and Overhead	1.6	9.4
Total Production Cost ($/BBL)	16.9	100.0

The cumulative effect of the biological and engineering improvements is to reduce unit costs to $16.9 per barrel. The theoretical best design system results in product costs substantially below the lowest market cost projection for crude wellhead petroleum of $42 per barrel (EIA, 1983).

The significant changes in the operational and cost input parameters in going from SOTA to theoretical best are summarized below.

Parameter	Input Values	
	SOTA	Theoretical
Lipid Content (%)	30	70
Culture Density (mg/L)	800	2200
Non Carbon Nutrient Recycle (%)	0	90
Carbon Dioxide Price ($ per metric tonne)	82.5	19.0*
Capacity Factor (days per year)	300	365

While other changes (e.g., increase in mixing and harvesting systems' efficiencies, year of commercial operation) also contribute to the decrease in unit cost, the parameters listed above had the largest effect. Lipid content and culture density increases result in increased output for the production facility, distributing annual costs over a larger volume. Recycling of non-carbon nutrients and a lower delivered price for CO_2 result in lower operational costs for nutrient supplies which represent over 50% of the annual variable costs for the state of the art production facility (see Table 3.0). The effect of these changes on unit production cost are discussed in the next section.

6.0 Sensitivity Analysis and Development of an Attainability Target for Microalgae Production

The purpose of this section is to determine those parameters which have the greatest influence on product costs. Based on this sensitivity analysis, one set of input values is specified which, in the judgment of ASP researchers, should be achievable by 1994.

6.1 Sensitivity Analysis

The sensitivity analysis has identified biological and engineering parameters which are most important in reducing microalgae unit cost, and has shown the areas in which intensive research activities should most significantly improve performance over state of the art levels. The parameters, productivity (culture or density), lipid content, nutrient recycling and lower nutrient supply prices and capacity factor, were systematically varied through a range of values between current state of the art and the theoretical best estimate. The entire range of values for each parameter was divided into quartile intervals to examine 25% improvements in each parameter and its effect on unit cost. A summary of the results of this analysis is presented in Table 5.0. Each input parameter, listed in descending order of importance, was varied between SOTA and theoretical best and a corresponding unit cost ($/BBL) was calculated. (All other parameters in the analysis model were held constant at SOTA values.) Lipid content is shown to have the most significant affect on unit cost. An increase in lipid content halfway towards the theoretical maximum results in a 40% decrease in unit cost compared to the SOTA value.

---

* Carbon cost at $19 per metric tonne of CO_2 (delivered) is based on an analysis of a report by the Colorado Energy Research Institute "Natural Carbon Dioxide Resources of Colorado: An Overview," October, 1982. This price for CO_2 represents a delivered cost of $1.0 per MSCF of$CO_2$ to a large end user similar to enhanced oil recovery.

Table 5.0 Effect of Quartile Improvements in Selected Input Assumptions and Their Influence on Microalgae Product Cost

Parameter	SOTA	Percentage Improvement 25	50	75	Theoretical Best
Lipid Content (%)	30	40	50	60	70
Unit Price ($/BBL)	(203.0)	(152.3)	(122.8)	(101.6)	(87.1)
Gross Productivity (g/m^3-d)	23.0	32.25	42.5	52.7	63.0
Unit Price ($/BBL)	(203.0)	(176.6)	(160.8)	(151.1)	(144.4)
Carbon Dioxide Price ($/mt)	82.4	66.5	50.6	34.8	19.0
Unit Price ($/BBL)	(203.0)	(185.5)	(167.8)	(150.3)	(132.8)
Non-Carbon Nutrient Recycle (%)	0	22.5	45	67.5	90
Unit Price ($/BBL)	(203.0)	(187.2)	(182.0)	(178.9)	(173.9)
Capacity Factor (days)	300	316	332	348	365
Unit Price ($/BBL)	(203.0)	(199.8)	(196.8)	(193.0)	(191.6)

From this table, lipid content, productivity and the delivered price of the carbon dioxide were determined to have the greatest effect on unit cost. Non-carbon nutrient recycling and capacity factors were less significant parameters.

One feature of analysis model, its handling of non-carbon recycling, provides an alternate way to interpret the results. To analyze the effects of nutrient recycling, unit price for the nutrient is reduced. A 22.5% recycling of non-carbon nutrients is equivalent to a 22.5% reduction in supplier prices for those nutrients. Therefore, the results presented for non-carbon nutrient recycling are also indicating the effects of lower contract prices for the nutrients, nitrogen, phosophous and potassium.

6.2 Attainability Target for 1994

The attainability target represents programmatic production cost goal for 1994, the year in which it is planned that capital funds will be expended for a large scale proof of concept experiment.

The major operational parameters utilized in establishing a 1994 attainability target are listed in Table 6.0. Economic parameters were assumed to be same as SOTA.

Table 6.0 Input Parameters Used to Define Unit Cost for the Attainability Target for 1994

Parameter	Value
Culture density (mg/L)	1500
Lipid content (%)	60
Carbohydrate content (%)	10
Recycling of non-carbon nutrients	90
Carbon dioxide price ($/mt)	38.5
Year of Commercial Operation	1998

With these assumptions, the annual net yield of algal biomass is 124 metric tons per hectare-year. Gross productivity is approximately 43.4 grams per square meter-day and the photosynthetic efficiency for the system is 13.2% of PAR. Levelized product cost for the 1994 attainability target is $55.6 per barrel. The distribution of annualized production costs is presented in Table 7.0

Table 7.0 Summary of Microalgae Production Costs for the 1994 Attainable Target

	$/BBL	% of Total
Annualized Capital Investment	11.8	21.2
Annual Operating Cost		
Utilities	8.7	15.6
Nutrients	26.6	47.8
O&M	3.2	5.6
Direct Labor and Overhead	5.3	9.5
Total Production Cost ($/BBL)	55.6	100.0

When compared with SOTA input assumptions for the raceway system, the attainability target presumes certain biological and engineering improvements by 1994 as a result of continued research in microalgal production systems. The improvements over SOTA defined parameters are: productively increased 90%; lipid content increased 100%; nutrient costs reduced by a factor of four through recycling; and carbon dioxide costs reduced through pipeline contracts by a factor of 2.5. Current laboratory experiments with microalgae indicate the necessary improvements are achievable, although large scale outdoor experiments are just beginning. Note that the parameters used to define the attainable biological target case represent but one solution set of a multivariable set of parameters. For example, improved operating efficiences would result in another solution set in which the biological performance requirements would be less.

The sensitivity analysis indicates that major cost or performance improvements in five areas will result in the cost reductions that are necessary for this technology to be competitive: Productivity, lipid content, nutrient recycle, operating costs, and capital costs. The first four of these areas are the major focus of the current microalgae research program. Research required for improvement in each of these areas is discussed below.

Biological

I. Productivity: Productivity or yield is a major cost sensitivity. The goal for 1994 is 134 dry metric tons/hectare-yr (gross yield). Four areas must be addressed to reach this goal.

   1. Species Selection - species must be selected that inherently are fast growers at high cell density.

   2. Applied Genetics - genetic systems must be characterized. Classical and modern genetic techniques can then be applied to improve the productivity of the selected species.

3. Culture Definition - culture conditions must be defined for each species of interest to obtain the maximal performance from the species. Both biological information (nutrients, light requirements, pH, temperature, salinity) and information on culture in outdoor facilities (detention time, mixing speed, depth) will be needed.

4. Culture Management Techniques - cultures must be transferred from the laboratory to the outdoors. The development of culture strategies and management techniques in outdoor facililties will result in further increases in productivity.

II. Lipid Content - Increase in lipid content is another major sensitivity. The goal for 1994 is the production of a biomass with 60% lipid content. Again four areas must be addressed to reach this goal.

1. Species Selection - species must be selected that inherently have the metabolism that provides for energy to be fixed into large quantities of oil products that are useful as fuels.

2. Applied Genetics - species which produce appropriate products can be screened through strain selection and classical genetics to improve the lipid content. Genetic manipulation of metabolic pathways and enzymes should also result in higher lipid contents.

3. Lipid Metabolism - the interrelationships between growth and lipid synthesis must be studied. Effective ways of triggering desired products will result. Knowledge of the effects of cell age, size, culture condition and stresses will result in a higher lipid content.

4. Culture Strategy - technology from the laboratory must be applied to outdoor culture to develop culture strategies that will result in higher lipid contents.

Biochemical Engineering:

I. Recycle of Nutrients: Presently the technolgy does not utilize a nutrient (nitrogen, phosphrous, carbon) scheme. By 1994 the goal is to recycle 90% of the nitrogen, potassium and phosphorous. Recycle is seen as the primary means of reducing nutrient costs, which are the major operating costs.

II. Operating Costs: Experience and research should reduce the operating costs by reductions in the harvesting power and circulation power requirements.

III. Capital Costs: Capital costs are also a major sensitivity. Reduction in capital costs may be brought about by development of innovative techniques for use of materials, low cost designs, etc.

References

1. Bassham, J. A.; "Energy Crops (Energy Farming)" in Biochemical and Photosynthetic Aspects of Energy Production, A. San Pietro (editor), Academic Press, 1980.

2. Beauparlant, J. R. "Natural Carbon Dioxide Resources of Colorado: An Overview" prepared by the Denver Research Institute, Univ. of Denver for the Colorado Energy Research Institute, October, 1982.

3. Benemann, J. R. et. al., "Microalgae as a Source of Liquid Fuels," prepared by Enkio, Inc. for U.S. Department of Energy's Office of Energy Research, Contract DEACOS 81 ER 30014; May 1982.

4. Benemann, J. R. et. al; "Production of Liquid Fuels and Chemicals by Microalgae" in Aquatic Species Program Review; Proceeding of the March 1983 Principal Investigators Meeting, SERI/CP-231-1946; June, 1983.

5. Burlew, J. S. (ed) "Algal Culture From Laboratory to Pilot Plant," Carnegie Institution of Washington-Publication 600, Washington, D.C. 1976.

6. Doane, J. W., et. al. "The Cost of Energy from Utility-Owned Solar Electric Systems; A Required Revenue Methodology for ERDA/EPRI Evaluations", Jet Propulsion Laboratory, JPL 5040-29, ERDA/JPL-10/2-76/3; June, 1976.

7. Energy Information Administration, "1982 Annual Energy Outlook with Projections to 1990", DOE/EIA-0383(83), April 1983.

8. Laws, E. A. and K. L. Terry "Shallow Algal Mass Culture Systems" in Aquatic Species Program Review; Proceedings of the March 1983 Principal Investigators Meeting, SERI/CP-231-1946, June 1983.

9. Lipinsky, E. S. et. al., "Systems Study of Vegatable Oils and Animal Fats for Use as Substitute and Emergency Diesel Fuels", prepared by Battelle-Columbus Laboratories for U.S. Department of Energy, DOE/NBB-0006; October 1981.

10. Mohn, F.H., "Experience and Strategies in The Recovery of Biomass from Mass Cultures of Microalgae" in Algal Biomass: Production and Use G. Shelef and C. J. Soeder, editors, Elesevier/North Holland Biomedical Press, 1980.

11. Nelson, S. H., An Investigation of the Availability of Carbon Dioxide for the Production of Microalgal Lipids in the Southwest; prepared by Argonne National Laboratory for the U.S. Department of Energy, Draft Report, November, 1982.

12. Oswald, W. J. and J. R. Benemann, "Algal-Bacterial Systems" in Biochemical and Photosynthetic Aspects of Energy Production," Anthony San Pietro (editor), Academic Press, 1980

APPENDIX A

Engineering and Economic Input Assumptions to Calculate SOTA and Theoretical Best Unit Cost for Microalgae Production.

Engineering Parameters	SOTA	Theoretical
Capacity Factor (days)	300	365
Harvester Subsystem Efficiency (%)	95	100
Facility Size (Hectares)	405	405
Nutrient Recycle	None	90% noncarbon nutrients
Economic Parameters		
Land Cost (per hectare)	$1,235	Same
Energy Costs (per kWh)	$.05	.05
Nitrogen Cost, per metric ton, (NH_3)	$203.0	Same
Carbon Cost, per metric ton (CO_2)	$82.5	$19.0 1)
Potassium Cost, per metric ton (KO_2)	$102.0	Same
Phosphorus Cost, per metric ton (superphosphate)	$281.6	Same
Investment Parameters		
Base Year for Constant Dollars	1983	Same
Year of Cost Information	1982	Same
Year of First Commercial Operation	1985	2000
Facility Lifetime (years)	30	Same
Depreciation Tax Life (years)	15	Same
Taxes, Insurance (each)	1% of Investment	Same
Income Tax Rate (%)	45	Same
Investment Tax Credit (%)	10	Same
Ratio of Debt to Capitalization (%)	50	Same
Ratio of Common Stock to Capitalization (%)	35	Same
Ratio of Preferred Stock to Capitalization (%)	15	Same
Annual Rate of Return on Debt (%)	3.7	Same
Annual Rate of Return on Common Stock (%)	5	Same
Annual Rate of Return on Preferred Stock (%)	4	Same
Real Escalation Rate on Capital Costs (%)	1	0%
Real Escalation Rate on Operating Costs (%)	1.5	0%
Calculated Parameters		
Cost of Capital (%)	3.4	Same
Capital Recovery Factor (Book Life) (%)	5.3	Same
Fixed Charge Rate (%)	7.4	Same

Note:
1) Carbon cost at $19 per metric tonne of CO_2 (delivered) is based on an analysis of a report by the Colorado Energy Research Institute "Natural Carbon Dioxide Resouces of Colorado: An Overview" October, 1982. This price for CO_2 represents a delivered cost of $1.0 per MSCF of CO_2 to a large end user similar to enhanced oil recovery.