DESIGN, FABRICATION, AND OPERATION OF INNOVATIVE MICROALGAE CULTURE EXPERIMENTS FOR THE PURPOSE OF PRODUCING FUELS

Final Report, Phase I

Contract #TK-3-03153-02

Aquaculture Associates, Inc.
1110 Richards St. #207
Honolulu, Hawaii 96813

ABSTRACT

A conceptual design was developed for a 1000-acre (water surface) algae culture facility for the production of fuels. The system is modeled after the shallow raceway system with mixing foils that is now being operated at the University of Hawaii. The facility takes advantage of the high yield and high cell density achieved in the shallow raceway system, as well as the unusual settling behavior of the proposed alga, Platymonas. A computer economic model was created to calculate the discounted breakeven price of algae or fuels produced by the culture facility. A sensitivity analysis was done to estimate the impact of changes in important biological, engineering, and financial parameters on product price.

In the baseline case for a facility in Hawaii, the discounted breakeven algae price is $366/MT dry weight ($398/MT AFDW) in the form of a 10% solids slurry. A case using more optimistic, but probably achievable, parameters reduced the price to $229/MT dry weight. The discounted breakeven price of methane produced from the algal slurry is $36/MSCF for the baseline case and $23/MSCF for the more optimistic case. These prices are probably too high for the facility to be viable on methane sales alone. A case in which credits are taken for shellfish grown on unharvestable algae in the facility's effluent demonstrated that byproduct sales can make a very substantial contribution to the economics of a large algae culture system. The discounted breakeven price for algae was $61/MT dry weight after credit was taken for shellfish sales.

A similar conceptual facility near the Salton Sea in California was also modeled. Algae from the California facility was less expensive than from the Hawaii facility because of geological CO_2 available at the Salton Sea site. Methane produced at the California facility would have a price similar to that in Hawaii because of the additional heating requirements for a digester in California.

A scaled experiment was proposed to test the concept of the large shallow-raceway culture facility. The experiment would have two stages: one to optimize raceway design, the second to test production, costs, labor, and maintenance requirements in raceways close to full production scale. Concurrent experiments at a New Mexico site would screen species to find ones appropriate for a U.S. Southwest version of the shallow raceway system.

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1.0 INTRODUCTION

Beginning with the "oil crisis" of the 1970's, microalgae have been under study as a source of renewable fuels. Microalgae in culture frequently have a higher efficiency of solar energy conversion than land plants. The ability of many microalgae to store a substantial proportion of cell mass as lipids has sparked interest in algae culture to replace liquid fuels, which are expected to become scarcer and more expensive.

In Hawaii, research on fuel production from algae began with Raymond (1978), who arrived at optimistic projections for oil production based on a small experimental system. Since 1980, SERI has funded a University of Hawaii study using a single 48 m^2 raceway and several smaller raceways to investigate the potential of a shallow raceway system. Distinctive features of this system besides the depth include high phytoplankton cell densities ($>10^7$ cells/ml), high water velocity (30 cm/sec), and mixing foil structures which create vortices in the flowing water. In dense cultures, the vortices expose algal cells to rapidly alternating light and dark periods, creating a "flashing light effect" that increases photosynthetic efficiency (Laws et al., 1983). The last year's research has increased production in the shallow raceway by the use of species adapted to the relatively high temperatures (30-35°C) in the Hawaiian raceway and the discovery that the dilution schedule has a strong effect on algal production. The shallow raceway now achieves yields substantially higher than those attained in other systems using inorganic nutrients (Laws, 1984).

In 1983 SERI issued a Solicitation for Letter of Interest to design a large-scale algae culture system for fuel production, and to propose a scaled experiment to validate the proposed design. Aquaculture Associates, Inc. (AAI) responded with a proposal based on the University of Hawaii raceway system. In April 1984 AAI was awarded one of three competitive design contracts.

1.1 Objectives

The overall objective of the project, as stated by SERI, was to develop a cost-effective design for a saline-water microalgae culture facility producing lipid fuels in the U.S. Southwest. Specific objectives of the subcontract were to:

1. Develop a conceptualized design for a large-scale raceway system at a site in Hawaii.
2. Develop a detailed design of an experimental system that would be appropriate for the Hawaiian site. not explicit
3. Develop an operating plan for the experimental facility.

4. Extrapolate the results of the Hawaiian facility to a site in the American Southwest.

Shortly after the project contracts were awarded, the requirement that algal lipids be the fuel source was relaxed, and consideration of any fuel product was permitted. It was also agreed that each contractor would report the price to produce an algal slurry of 10% solids content in order to allow comparisons among systems that would produce different fuel products.

1.2 Project Participants

Participants in this study were:

Management and Biology: Aquaculture Associates, Inc.

Subcontractor (Engineering): Makai Ocean Engineering, Inc.

Subcontractor (Foil Studies): Hawaii Natural Energy Institute

Consultant (Algae Culture): Dr. Edward Laws, University of Hawaii

Consultant (Economics): Dr. Karl Samples, University of Hawaii

Consultant (Harvest Technology): Dr. Gary Rogers, University of Hawaii

2.0 PRELIMINARY ANALYSIS

Before a baseline algae farm design could be attempted, it was necessary to determine which components of the farm were the most important cost drivers. Engineering aspects of a shallow raceway system with foils were studied to discover potential limitations on raceway length, width, and depth and to model water circulation costs as a function of raceway design. Flume studies were done to estimate what foil spacing might be adequate to produce the desired turbulence at minimum cost. Choices had to be made among different algal species, harvesting methods, and processing options.

After the basic elements of the conceptual facility were defined, a preliminary economic model of the facility was constructed. The model was used to determine which design and cost parameters were most critical to the cost of algae produced in the facility. Design effort was then concentrated on the items found to be most important to algae production cost. When the final facility design was completed, cost estimates for facility components were refined and a final "baseline" version of the economic model was prepared for use in sensitivity analysis.

The following sections describe the preliminary engineering and economic analysis.

2.1 Engineering Model of Raceway

Shallow, high velocity in contrast
To EnBio

The shallow raceway system chosen for this study differs hydraulically from the deeper ponds previously used for algal mass culture studies. In addition to being shallower (8-12 cm vs. approximately 20 cm), the UH experimental raceway has a higher water velocity (30 cm/sec) than most other open culture systems (e.g. Benemann et al., 1982). The UH raceway also uses foil structures at intervals throughout the raceway to create ordered turbulence which increases production rates (Laws et al., 1983). All of these characteristics influence the amount of energy which must be used to circulate the water in the raceway. An engineering study (Appendix 1) was conducted by MOE on the effects of various raceway and foil design parameters on raceway circulation. The objectives of the study were to:

1. Determine effects of raceway parameters on utility costs for water circulation and mixing;

2. Determine the importance of utility costs relative to other operating costs such as nutrient requirements;

3. Determine head losses along the raceway to guide raceway design.

Parameters considered were:

1. Raceway water depth
2. Raceway width
3. Raceway length
4. Water velocity
5. Bottom surface roughness (friction factor)
6. Circulation pump efficiency
7. Mixing foils
    a. Drag coefficient
    b. Distance between foil rows

Among the conclusions of the study were:

1. Water velocity is the most important parameter influencing circulation power requirement.
2. Friction factor and foil angle are both important to power consumption and head loss.
3. Increasing the distance between foil sections is important to both power consumption and head loss reduction.
4. If raceway width is much greater than raceway depth, an increase in depth will result in a slight decrease in power consumption and head loss. Therefore, from the standpoint of utility costs, it is desirable to set raceway depth near the high end of the acceptable range.
5. If the raceway width is at least 30 times greater than the depth, the effect of width on power consumption per unit area is minimal.

These results were taken into account during subsequent facility design. The relationships derived during this study were included in the computer model of the facility so that the model could determine utility costs for a range of design assumptions.

The preliminary engineering study was unable to define any maximum width or length for the raceways based purely on considerations of power consumption and head loss. It also was not designed to determine the actual effects of raceway design parameters, foil designs, and pump types on algal productivity; knowledge of these effects requires further experimentation.

← namely what?

2.2 Mixing Foil Flume Experiments

The mixing foils in the UH experimental raceway are intended to create a pattern of vortices in the raceway water flow, alternately submerging and raising the algal cells. In a dense culture, the cells are exposed to alternating light and darkness. The effect of the "flashing light" is to increase the photosynthetic efficiency, and therefore the yield, of the algae. Terry (1985) found that under laboratory conditions, flashing light of 1-2 seconds duration enhanced photosynthetic efficiency in Phaeodactylum tricornutum because the cells responded to the average light intensity received rather than the flash intensity. The foils might also increase production for other reasons, such as increased turbulence, as well as by light modulation. The foils have increased production by 45-100% vs. the same raceway without foils in experiments at the Hawaii experimental raceway (Laws et al., 1983; SERI Biomass Program Monthly Report, January 1985).

In early experiments in the Hawaii raceway system, the foils were shaped like small airfoils (Laws et al., 1983). The system now uses flat, notched plates because of their low cost and ease of construction. (In this report, the term "foil" is used to indicate any of these turbulence-producing devices regardless of shape.) There is little experimental data to define an "optimal" foil design or spacing. Since a conceptual culture system based on the experimental raceway will require many foils, it was assumed that foil costs would be significant and that some estimate of foil spacing would be required for the raceway cost estimates. Experiments were therefore conducted to gain some knowledge of the turbulence created by simple foil shapes at different spacings. These experiments helped to define the range of foil spacings that might be acceptable in the conceptual facility.

The experiments were conducted by HNEI personnel in a flume at the University of Hawaii (Appendix 2). Square and triangular foil plates were tested at a water velocity of 30 cm/sec. Measurements of velocity profiles through the water column beyond the foils indicated that turbulence may extend 2-5 m beyond the foils. A 3-m spacing was selected for the baseline facility model. The experiments also suggested that a wider lateral spacing of the foils (requiring fewer foil plates) could produce adequate mixing compared to the present lateral spacing in the experimental raceway. This possibility was investigated as a special case during the sensitivity analysis of algae costs.

2.3 Species Selection

The selection of an algal species for the conceptual culture facility is critical because it defines many of the operating parameters of the system, e.g. water exchange frequency, nutrient requirements, and potential energy products. Species selection is in turn influenced by characteristics of the chosen farm site such as temperature range, salinity, and presence of competing species. In addition, the chosen species must be compatible with the type of culture system desired. This latter requirement is critical for the purposes of this report because the type of culture system has already been chosen: a shallow raceway system with photosynthetic enhancement using foils.

Despite these restrictions, most microalgae are potential candidates for the conceptual culture system because there are so many species and so little is known about them. Biochemical and genetic modification of existing algae could (in theory) create "superalgae" that are adapted for a particular system and produce large quantities of a particularly desirable product. Key assumptions of the baseline analysis are that no such genetic or biochemical advances are achieved and that only species known to thrive in the existing shallow raceway can be considered. These assumptions are conservative, and may lead to a substantial underestimate of the potential of the conceptual system. Without them, however, the characteristics of the chosen species would be so nebulous that the facility model might have little predictive value.

Only four or five algal species have been cultured in the experimental shallow raceway system because it is a relatively new system. Of the algae that have been tried, two have been grown successfully at high production rates: Platymonas sp., a motile green alga, and Chaetoceros gracilis, a diatom. Both species have exhibited sustained production rates exceeding 40 g AFDW/m^2-day in the Hawaii experimental raceway (Laws, 1984; SERI Biomass Program Monthly Report, October 1984). Platymonas was chosen over Chaetoceros because it appeared to have the best combination of desirable traits:

1. Platymonas has exhibited slightly higher production rates in the experimental raceway.

2. Platymonas is a dominant species, resistant to competitors and predators in the Hawaii shallow raceway system.

3. Chaetoceros requires silicate and vitamin additions (Laws, 1984); Platymonas does not.

4. Platymonas apparently can be harvested simply and with little energy expenditure because of its settling behavior (see below); Chaetoceros does not appear to settle rapidly and would require more expensive means of harvesting.

5. Under optimal culture conditions as defined so far in the experimental raceway, Platymonas requires less total water exchange than Chaetoceros (Laws, 1984; SERI Biomass Program Monthly Report, October 1984).

The major disadvantage of Platymonas is that its storage product is carbohydrate rather than lipid. To date, the SERI fuels-from-microalgae program has focused strongly on lipid-derived fuels because of their relatively high value. It is therefore desirable to present a rationale for accepting a species that is not noted for its ability to produce lipids.

When microalgae are growing rapidly (not nutrient-limited) they store little lipid (Goldman, 1980); both Platymonas and Chaetoceros in the shallow raceway system contain about 15-20% lipid. Most of the lipids in rapidly growing algae are membrane-bound lipids that are unsuitable for fuel use without special processing (Tornabene, 1984). In order to induce microalgae to produce large amounts of the more desirable storage lipids, it has been necessary to expose them to nutrient limitation for periods of several days. During this period, algal growth slows down; because of this growth slowdown, total energy production usually declines even though the energy content of the cells themselves rises (Lien and Spencer, 1984).

Reduced total energy production might be tolerable if the algal lipids could be processed easily and cheaply into usable fuels. Unfortunately, this may not be the case. Present industrial techniques for extracting lipids from biomass are applied to dried crops raised on land, but harvested algae will be mostly water. Existing dewatering techniques are probably too expensive for an energy product (see Appendix 3); considering the heat of vaporization of water, heat drying of a 10-20% solids content slurry would require about as much energy as is contained in the algae. Solar drying is possible, but is not totally reliable. At published rates of solar drying (e.g. Venkataraman et al., 1980) an area at least equal to the total growing surface of the farm would be necessary to dry a day's algae production. Systems would have to be developed for spreading a thin layer of algal slurry over hundreds of hectares of some acceptable substrate, and for collecting the dried material economically.

An alternative to drying is wet processing of the algae. There appear to be two major processes for lipid extraction: solvent extraction and supercritical carbon dioxide extraction. Supercritical carbon dioxide extraction may not work on wet biomass because the CO_2 reacts with water at high pressure, forming strong acids that attack the organic material (M. Antal, University of Hawaii, pers. comm.). Solvent extraction is potentially feasible for wet materials, but would probably be more expensive than for dry feedstocks because a relatively large quantity of slurry at relatively low lipid content would have to be processed. The range of potential solvents may be limited because solvents that can mix with water will be expensive to recover from the effluent stream. A significant portion of the algal lipids will be membrane lipids which may require a different solvent, and which will need to be processed further before they can be used as fuel. One estimate of the cost of transesterification, which can convert algal lipids to fuels resembling diesel fuel, is $1.41/gallon exclusive of algae cost

(Hill and Feinberg, 1984). Finally, the output of a single 1000-acre algae farm is too small to take full advantage of economies of scale in extraction and processing (Hill et al., 1984).

The above discussion is not meant to imply that the concept of deriving fuels from algal lipids is infeasible. Research into algal lipid production, harvest techniques, and extraction/processing methods may greatly improve lipid fuel economics. This analysis merely notes that the engineering and economic parameters of a lipid fuel production system are highly uncertain and would make it difficult to predict the economic feasibility of the algae culture system. Since the main task of this report is to evaluate the economics of producing and harvesting microalgae, little effort ~~could be spent studying~~ extraction and processing methods. but, direction is still fuels so success potential must be questioned

2.4 Harvest Experiments

Because of the small size of microalgal cells, harvesting has always been one of the major issues in algal mass culture technology (Mohn, 1980). A variety of harvest techniques has been tried over the past 30 to 40 years (e.g. Mohn, 1980; Shelef et al., 1984; also see Appendix 3); most have proved inefficient or too expensive and energy-intensive for all but the most valuable algal products. Harvestability is therefore a major criterion for selection of an algal species for mass culture, although in practice species have usually been selected for their growth rate, production of valuable compounds, or resistance to competition and predators.

One of the reasons Platymonas was selected as the species to be cultured in the conceptual facility is its reported settling behavior in the experimental raceway in Hawaii. Technical personnel reported that Platymonas cells settle rapidly in flasks, and must be resuspended so that the cells can be counted. In addition, if a power failure occurs and raceway circulation stops for several hours, the cells settle to the bottom of the raceway (L. Pang, pers. comm.). Walne (1970) reported that species of Tetraselmis (= Platymonas) settled rapidly when placed in containers, but regained their swimming behavior in about 24 hours. The possibility that Platymonas could be harvested by simple settling justified the several experiments that are described below.

Initial settling experiments with Platymonas used Imhoff cones, which are conical graduated vessels commonly used to measure suspended solids. Although Imhoff cones have been used in the past to measure settling of algal solids (Benemann et al., 1980), they proved to be poor devices for inducing settling in Platymonas. Some of the algae flocculated and settled, but most remained suspended. Subsequent experiments were conducted in Erlenmeyer flasks. These experiments were much more successful; cell counts showed that 80-90% of Platymonas cells settled to the bottom within 24 hours. Apparently the shape of the container affects settling in *Platymonas*, at least in small vessels. Settling appeared to be slightly less complete in flasks covered with foil than in those exposed to ambient (indoor) lighting, but too few experiments were done to demonstrate significance of this observation.

To confirm the harvestability of cultured *Platymonas* on a larger scale, a 55-gallon drum with one end removed was used as a settling tank. The tank was filled with a suspension of *Platymonas* (approx. 10^7 cells/ml) harvested from the experimental raceway as a part of normal raceway operations. Approximately 24 hours later, samples were taken from the top, center, and near the bottom of the water column for cell counts. Then the water was drained slowly from the drum. When as much water as possible had been drained, the drum was tilted slightly to allow remaining water to run off the viscous sludge at the bottom of the drum. A sample of the sludge was scraped from the bottom and weighed, then dried to determine solids content.

Two settling drum experiments were done. In the first trial, approximately 82% of the cells originally present in the harvest water settled to the bottom. The solids content of the harvested sludge (after subtracting the presumed weight of the salt present) was a surprisingly high 13.5%. In the second trial, approximately 90% of the cells settled out and the sludge solids content was 7.1%. The supernatant water from this trial had a pH of 7.3 at the end of the 24-hour period, suggesting that high-pH induction of flocculation (Arad et al., 1980) is not critical to the settling process.

circumstantial evidence

Benemann et al. (1980) reported that under certain culture conditions, rapid bioflocculation occurs in *Micractinium* with similar settling time and removal efficiency to the settling exhibited by *Platymonas* in the recent experiment. However, the solids concentration of the settled *Platymonas* seems to be much higher than that of *Micractinium*. Electron micrographs indicated that *Micractinium* aggregates by means of extracellular filaments; micrographs of settled *Platymonas* might reveal whether or not its settling mechanism is similar. Koopman et al. (1980) suggest that bioflocculation is encouraged by high pH and low nitrogen levels, but these conditions are not normally present in the Hawaii experimental raceway.

? in experiments

In summary, *Platymonas* exhibits rapid settling which, in a properly designed settling tank or pond, may allow harvesting at minimal energy cost. Harvest efficiencies of 80-90% and solids concentrations exceeding 7% may be achieved with a 24-hour settling period. These few experiments do not demonstrate that rapid settling of *Platymonas* occurs consistently under all culture conditions, or that settling occurs as rapidly and efficiently in a large settling pond as in smaller containers. Experiments to answer these questions are proposed for the scaled experiment.

2.5 Processing Options

Emphasis in this study has been directed towards estimating the potential price of algal biomass produced in a shallow raceway system, but a secondary task is to estimate the breakeven price of a particular fuel product derived from the algae. Proper selection of a processing method can reduce the overall cost of algae production if essential nutrients can be recycled to the production facility. An appropriate processing system should have the following characteristics:

1. It should be suitable for the chemical composition and water content of the algal feedstock;
2. It should be as efficient as possible in converting algal biomass into fuel;
3. It should allow maximum recycling of nutrients;
4. It should be a relatively well-known process, so that reasonable cost estimates can be made.

Two fuel-producing processes appear best suited to the characteristics of an algal slurry: fermentation to ethanol and anaerobic digestion to methane. Anaerobic digestion seems to be the more promising of the two processes for algal fuel production (Hill et al., 1984) and was chosen for economic modeling studies.

Another process, supercritical water oxidation, was also modeled briefly as an algae-to-energy system. Although the output of this system is electricity rather than a fuel, it represents one way algal biomass might be used to displace some of the fossil fuels now used in electricity production. Its use in energy production is not yet well developed, but it seems to have the potential to use a somewhat higher-cost algal feedstock than fuel-production processes because the total energy content of the algae is used at high efficiency. The system is ideal for using a wet feedstock and avoids some of the problems (such as sludge disposal) associated with fuel conversion.

2.6 Economic Model Development

Once a basic facility design existed, a spreadsheet-based computer model could be developed. The model combines biological, engineering, environmental, and cost parameters to calculate capital and operating costs for the conceptual facility design (Figures 2-1 and 2-2). The financial section of the model takes these costs and calculates the discounted breakeven price of the algae (or fuel product) as described below. The model is designed to be flexible; the spreadsheet design accepts parametric changes easily.

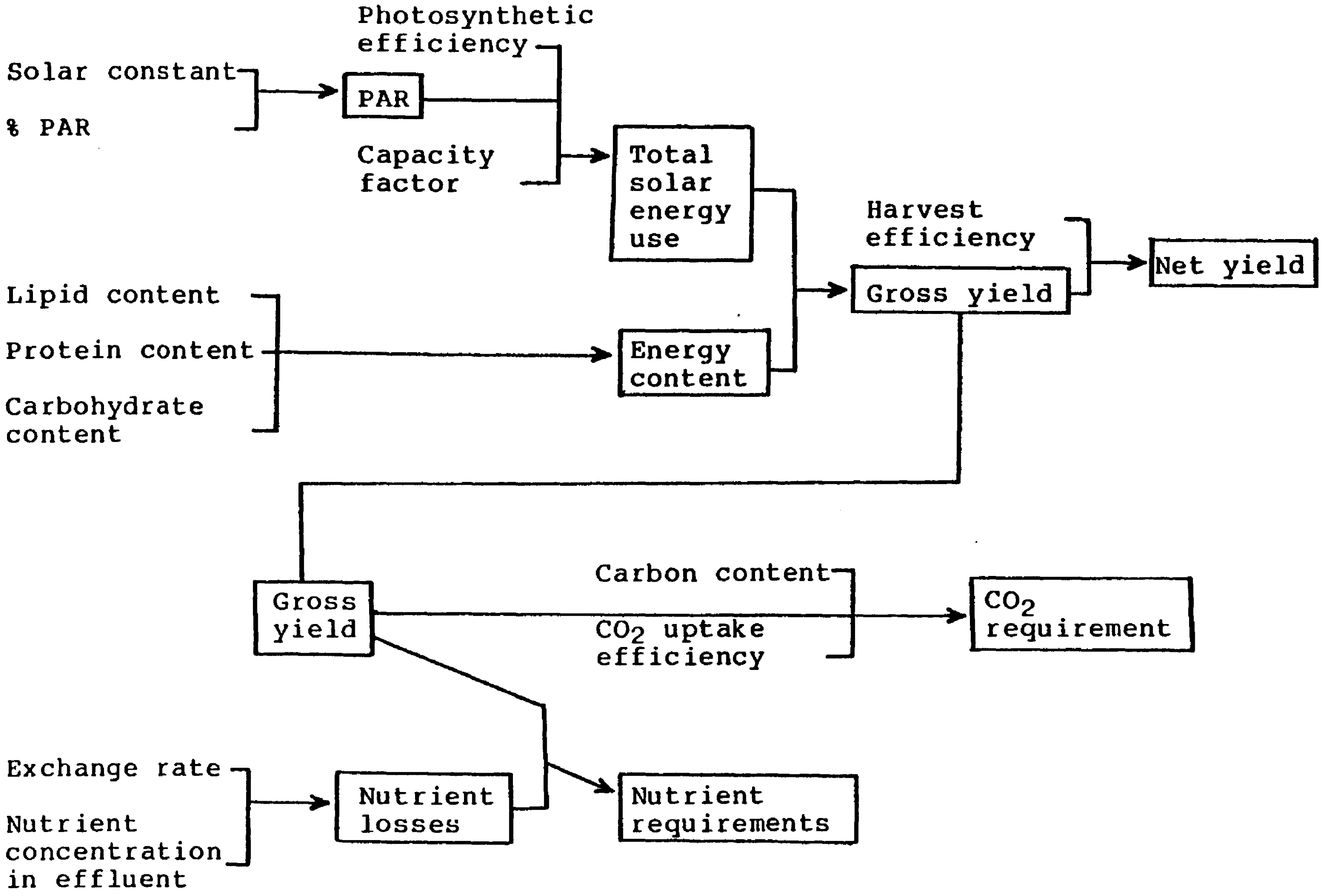


Figure 2-1. Flowchart of biological section of algae facility model. Parameters in boxes are calculated by the model; others are input parameters.

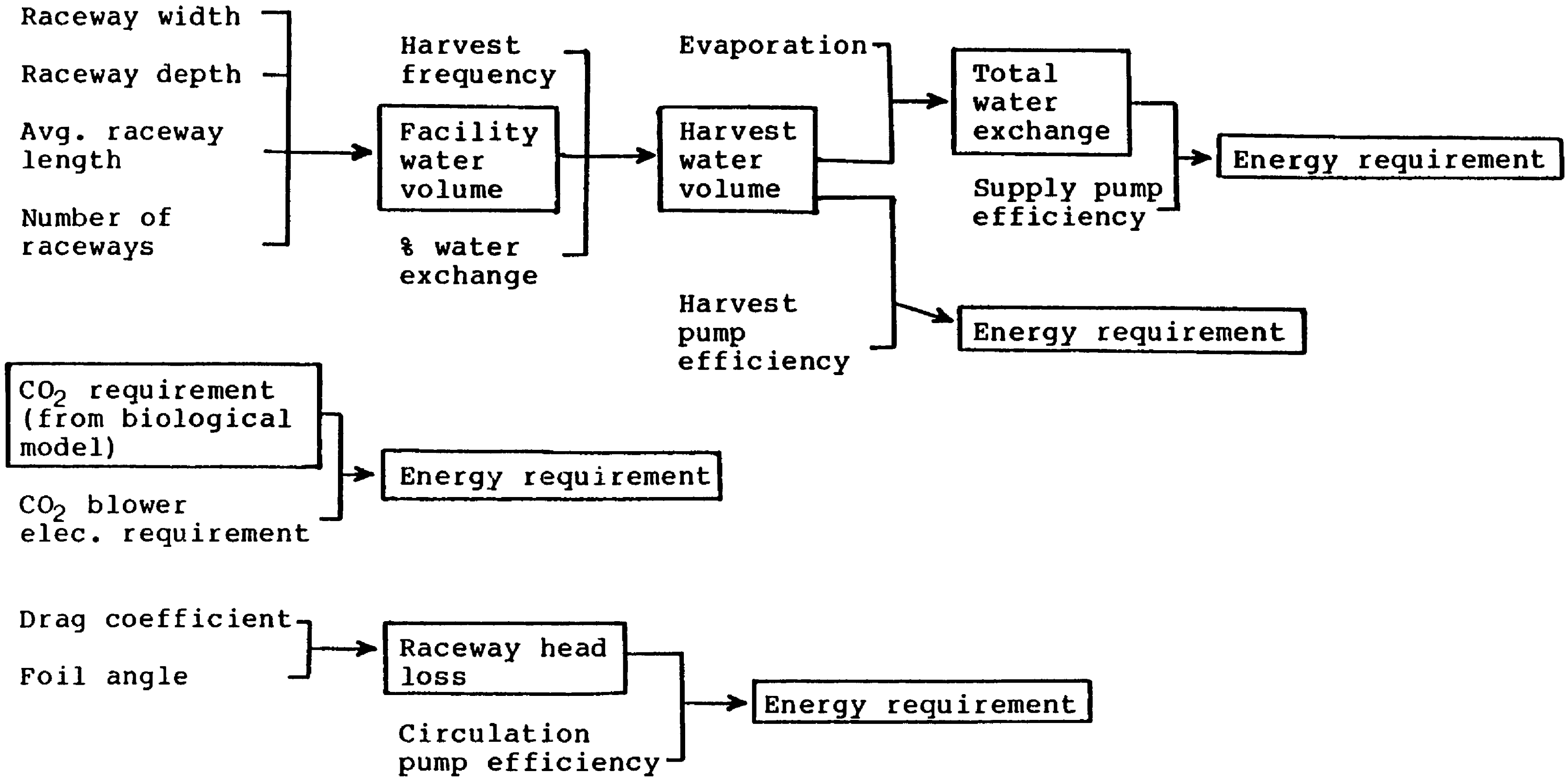


Figure 2-2. Flowchart of engineering section of algae facility model. Parameters in boxes are calculated by the model; others are input parameters.

IROR = COC

2.6.1 Overview of Financial Model

The financial model is designed to solve for a unit algae price ($/metric ton) that will be charged for all algae produced during the project lifetime. The calculated price affords just enough revenue so that the present value of the stream of revenue inflows exactly equals the present value of all cost outflows, including costs associated with borrowed and equity capital. Alternatively stated, the price is just sufficient to keep the present value of net cash flow at zero when the discount rate equals the weighted cost of equity capital. Costs, including opportunity costs of capital, are just covered by revenue inflows and zero excess profit is generated. Furthermore, at this price, the internal rate of return exactly equals the weighted cost of equity capital.

Let this price be called the discounted breakeven price. Expressed simply, the formula for its calculation is:

$$\text{DBEP} = \frac{\sum_{t=1}^{T} OF_t/(1+d)^t \; - \; S/(1+d)^T}{\sum_{t=1}^{T} Q_t} \tag{2.1}$$

where:

OF_t = cash outflow in time t
Q_t = algae production in time t
S = salvage value
T = project termination date
d = weighted cost of equity capital

SERI uses this method

Calculation of DBEP can be accomplished using information on average annual capital and operating costs, or by using a multi-period cash flow model. In this project, a discounted breakeven price is derived using a multi-period model. This method contrasts with SERI's revenue requirement economic model that calculates DBEP by annualizing capital and operating costs. A multi-period model is preferred over an average annual model for three basic reasons. First, because the time value of money is positive, the timing of revenues and costs can affect net present value of cash flow, and thereby the DBEP. If the timing of revenues and costs can be specified relatively accurately, then the actual cost and revenue time stream should be used in analysis rather than average annual costs because the resulting assessment will be more accurate. Secondly, a multi-period model allows the time stream of taxes, loss carryovers and investment tax credits to be more accurately incorporated into the financial analysis. Third, by using a multi-period model the financial effects of different leveraging strategies can be interpreted more accurately. Fourth, use of a multi-period model permits more accurate representation of financial effects of variable rates of inflation, cost escalations, and costs of capital throughout the project lifetime.

2.6.2 Cash Flow Description

A 25-year cash flow model is used to calculate DBEP. Parameter inputs into the model come from two sources. One source is financial parameters specified by the user. A second set of parameters is calculated earlier in the production and costing parts of the model. The objective of the model is to determine a price which makes the present value of a net cash flow stream equal to zero, where net cash flow is the difference between cash inflows and outflows.

Cash inflows come from selling farm outputs in competitive markets. It is assumed that all outputs are sold at constant prices with zero marketing costs. Revenues from the sales of algae are defined as the quantity of algae produced multiplied by the calculated DBEP. Quantity of algae produced is a calculated variable coming from the biological and engineering portions of the model. DBEP is calculated internally in the model using an iterative calculation algorithm. If sales of byproducts are included in the model, their contribution to cash inflow is added to algae sales. Byproduct credits reduce the algae revenue needed to offset project costs.

Cash outflows in time t are defined as:

$$OF_t = OC_t + DS_t + T_t + EI_t \qquad (2.2)$$

where:

OC_t = operating costs in time t
DS_t = dept service in time t
T_t = taxes paid in time t
EI_t = equity injections in time t

Cash outflows are associated with the equity portion of initial capital costs, principal and interest of funds borrowed to finance the balance of initial capital costs, annual operating and maintenance costs, and income taxes. A large part of cash outflow is tied to initial capital costs which include construction, material/equipment procurement costs along with engineering and contingency (including working capital) funds. Initial capital costs enter into cash outflow in two ways. The portion funded by stockholders' equity contributions is considered an outflow in the first period. The portion funded by borrowed capital is charged as an annual outflow (loan principal) from the first period until the last. Subsequent capital injections, for example replacement expenses, can be treated as either capital or operating cost outflows. In the model, replacement costs are treated as additions to operating costs rather than new capital injections. This treatment simplifies the model but it tends to understate the present value of cash outflows because of distortions in the time stream of tax liability. By charging replacements as operating costs, taxes are smaller in the year that the replacements occur than would be the case if replacement costs were annualized as depreciation.

Operating costs are direct expenses associated with growing algae and maintaining capital in a operating condition. Operating costs have a fixed and variable component. Fixed charges such as for rent, insurance and administrative overhead are input parameters. Variable costs such as for electricity, labor and nutrients vary with the quantity of algae produced annually. All operating costs are expressed in terms of 1984 dollars in the model. No inflation or cost escalation is assumed.

Interest payments constitute a significant annual cash outflow that decreases in absolute size during the project period. Interest charges in time t equal the real (inflation-adjusted) simple annual interest rate on the debt portion of capital multiplied by the loan balance outstanding at the end of time t.

The final component of cash outflow is state and federal taxes. The model is relatively sophisticated in the treatment of tax calculation. Federal taxes are paid on all net income after depreciation, interest, state taxes and all operating costs have been appropriately deducted from revenue inflows. A multi-period model has the advantage that depreciation can be treated according to any number of possible depreciation schedules. For purposes of our analysis, a conservative straight line depreciation schedule is adhered to. Current IRS guidelines are used to identify depreciable and non-depreciable components of initial capital costs. Almost all initial costs qualify for depreciation except land preparation, roads, engineering and contingency funds (including working capital funds) and permit fees. The depreciable portion of initial capital costs is annualized by simply dividing by 25, the specified project lifetime. State income taxes are calculated according to existing marginal tax rates on operating profits, just as is federal tax liability. The tax portion of the model assumes that the farm is operated as a corporation. In years when operating losses occur, these amounts are automatically carried over to subsequent periods to offset operating profits. Investment tax credit (ITC) is used to offset federal tax liability. Current IRS guidelines regarding allowable ITC calculation procedures are followed. This means that maximum allowable limits on ITC (relative to tax liability) are followed, and credits are only included for qualified capital investments. In years where federal tax liability is less than ITC available, the balance of ITC is carried over to subsequent years.

2.6.3 Treatment of Salvage Values

As shown in Equation 2.1, calculation of DBEP is contingent on whether or not capital will be salvaged at the termination of the project. Throughout our analysis, zero salvage values are assumed for two reasons. First, the bulk of the fixed investment is in structures that have few, if any, alternative uses. Secondly, the structures are maintained in such a way that they would expectedly be in poor condition at the end of the project. Salvage values would consequently be low.

2.6.4 Choice of Discount Factor

The discount factor used to equate the present value of cash inflows with outflows is a key ingredient in the model. The appropriate discount rate is the weighted cost of equity capital expressed as:

$$d = [R_p/(R_p+R_c)] + [R_c/(R_p+R_c)] - I \qquad (2.3)$$

where:

R_p= ratio of preferred stock
R_c= ratio of common stock
I =expected inflation rate

Expressed in this way, the discount rate is the real (inflation-adjusted) weighted rate of return to stockholders. It is weighted by the relative shares of preferred and common stock in initial capitalization. The expected inflation rate is deducted from nominal returns to stockholders to account for the fact that the model is expressed in terms of 1984 constant dollars.

2.6.5 Calculation of Discounted Breakeven Price

Calculation of DBEP is done in a circular manner in the model. This is done because DBEP is a function of the time stream of taxes, and tax calculation requires information on cash inflows which are themselves functions of DPEP. DBEP estimation is accomplished using an iterative recursive calculation algorithm. Given a starting value for DBEP, revenues and costs are calculated. State and federal taxes can then be estimated. If the present value of net cash flow is then found to be different from zero (given a specified minimum convergence difference), then adjustments in DBEP are made and recalculation occurs. Convergence is normally achieved within 6 iterations depending on the starting value selected.

The breakeven price that is finally estimated is expressed in terms of 1984 dollars. This is because the financial part of the model is expressed in terms of constant (inflation-adjusted) dollars. To calculate what the breakeven price would be in a later period, all that one needs to do is project inflation and real cost escalation rates and adjust DBEP accordingly.

3.0 CONCEPTUAL DESIGN: HAWAII FACILITY

A major problem in the conceptual design of a commercial microalgae production facility is the lack of a clear understanding of the factors influencing the growth of microalgae. It is very easy to ask questions for which there are no answers, either in the form of a developed theory or experimental data, especially when the answers may depend on the species of alga to be grown. Such questions include the effect of water flow velocity on production; the effect of pump type, i.e. paddlewheel versus propeller pump versus airlift pump, on production; the mixing foil growth mechanism and the effects of changing the spacing of the mixing foils with respect to the width and length of the raceway; and the precise relationship between CO_2 and nutrient distribution and production. Lacking answers to these and many other questions, a conceptual design of a commercial facility is based on many assumptions and can only parallel established, successful experimental practices. The conceptual design described in this report imitates the University of Hawaii experimental system in several ways:

1. Raceway water depth is limited to 12 cm.
2. Baseline flow velocity is 30 cm/sec.
3. Mixing foils are placed at a mid-point in the flowing water column, although at a lower density than the experimental system currently employs.
4. CO_2 is diffused into the water in a U-tube system similar in principle to that currently employed by the experimental facility.
5. The microalgal species _Platymonas_ grows at a photosynthetic efficiency of about 12% of PAR (assuming PAR = 45% of total insolation).
6. _Platymonas_ is grown on a 3-day cycle; every 3 days 87% of the water in a raceway is harvested and replaced with new well water.

Several other assumptions were made that have a major impact on the overall facility design. These assumptions include: Harvesting and refilling of raceways can be carried out 24 hours a day, seven days a week. The raceway circulation head loss is 8 cm per 100 m (Figure 3-1). Finally, it is assumed that low rpm propeller pumps can be used for raceway water circulation without harming or limiting the growth of the microalgae.

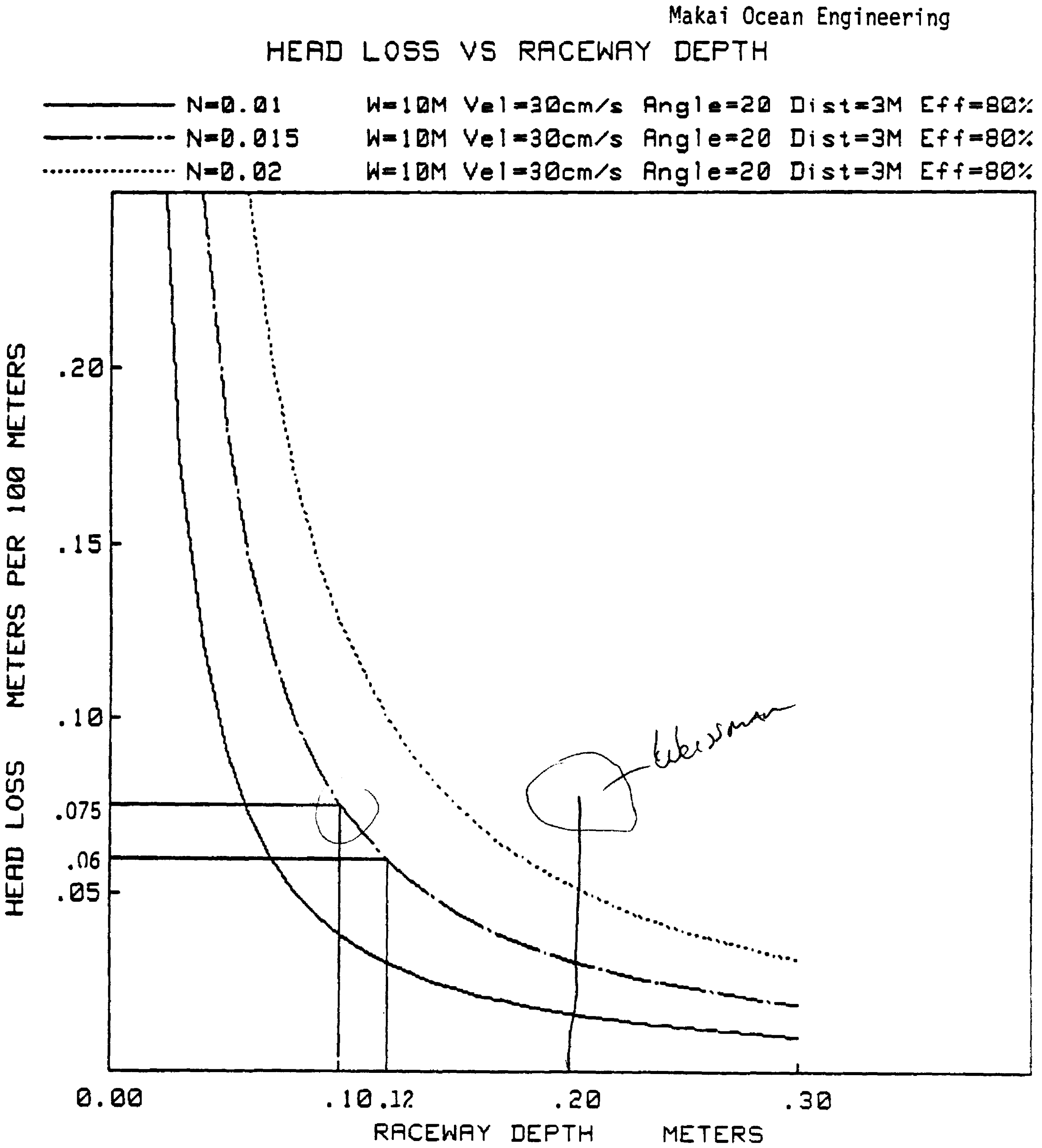


Figure 3-1. Theoretically predicted head loss vs. raceway depth for the Hawaiian commercial raceway design.

3.1 Design Criteria

Based on preliminary analysis using the facility economic model described above, it was determined that facility capital costs were the most important cost driver in the initial facility design. Among the parameters tested for sensitivity in the preliminary analysis, it was found that the costs of the raceway liners and the mixing foils were the most important capital costs. These results were not unexpected. In a 1000 acre commercial facility, over 43,000,000 square feet of pond liner material will be required. The cost of the liner per square foot will obviously be very important to the overall cost of the facility. Mixing foils are likewise a very high volume capital cost item. Using the same foil density as found in the Hawaii experimental raceway, approximately 15,000,000 individual foil segments would be required for a 1000 acre facility; at the proposed baseline density, about half that number would be required. Other cost drivers that were important in the preliminary analysis include harvester (settling pond) construction costs and CO_2 costs. Acknowledging these items as most important to the cost of the overall facility, the primary criteria which guided later facility design were:

15×10^6 foils

1. Construction of a raceway that can use a low cost, low maintenance pond liner material.
2. Design of a mixing foil that is inexpensive to construct, install, and maintain and has a long life.
3. Design of a less expensive settling pond.
4. Design of a CO_2 delivery system that maximizes the CO_2 uptake efficiency at minimum cost.

Wherever possible other facility capital costs were also minimized, but primary design efforts concentrated on the above objectives.

3.2 Site Selection

The generally accepted requirements for selecting a site for construction of a commercial microalgae facility are listed below:

1. The site must have high solar radiation levels.
2. The site must have an available water resource of a type and quantity appropriate for raising the phytoplankton species desired.
3. The site must be close enough to a source of CO_2 or flue gas to allow economical exploitation of this resource.

4. The land on which the facility is built must be inexpensive and be available for sale or long-term lease.

5. Considering the large volumes of earth which must be moved to construct such a facility, it is highly desirable that the soil be free from large outcroppings and be of adequate depth to facilitate economical earth moving operations. (This final point is not an absolute requirement but should be considered a tradeoff in evaluating sites with different surface geologies.)

The site selected for the Hawaii-based conceptual design is located near the southwest corner of the island of Oahu, west of Pearl Harbor, on land owned by the Campbell Estate and leased by the Oahu Sugar Company. Figure 3-2 outlines the boundaries of the site, which is between Barbers Point Naval Air Station on the west and West Loch Naval Reservation and Ewa Beach on the east. This site was selected because it satisfies all the above requirements. An Oahu Sugar Company representative, Bert Hatton, reported that Oahu Sugar would be willing to negotiate a lease arrangement with an algae aquaculture facility.

The Oahu Sugar site is currently under sugar cane cultivation. However, the land is considered marginal for this use and may be removed from active cultivation if the economics of sugar production do not improve. To aid in the calculation of construction costs, it is assumed that algae farm construction begins shortly after a cane harvest, so that only cane stubble need be cleared away.

Vacant land at the Barbers Point Naval Air Station and the West Loch Naval Reservation were considered as potential sites as well. However, in discussions with Navy real estate officials, it was learned that these vacant properties could be used only for much lower intensity agricultural activities such as truck farming or cattle grazing since both areas fall under the restrictions of military blast zones which surround buried munitions dumps.

The island of Hawaii has much more land area potentially available for algae cultivation than does Oahu, but lacks a large, inexpensive supply of carbon dioxide. This limitation precluded detailed consideration of a site on the island of Hawaii.

3.3 Facility Layout

Figure 3-3 illustrates the overall layout of the commercial facility design on the Oahu Sugar Site. Seawater wells are located as close as possible to the seashore, limited only by the State shoreline setback line which prohibits construction directly on the ocean front. The coral caprock which can be found 2 to 10 feet below the soil surface in this area is

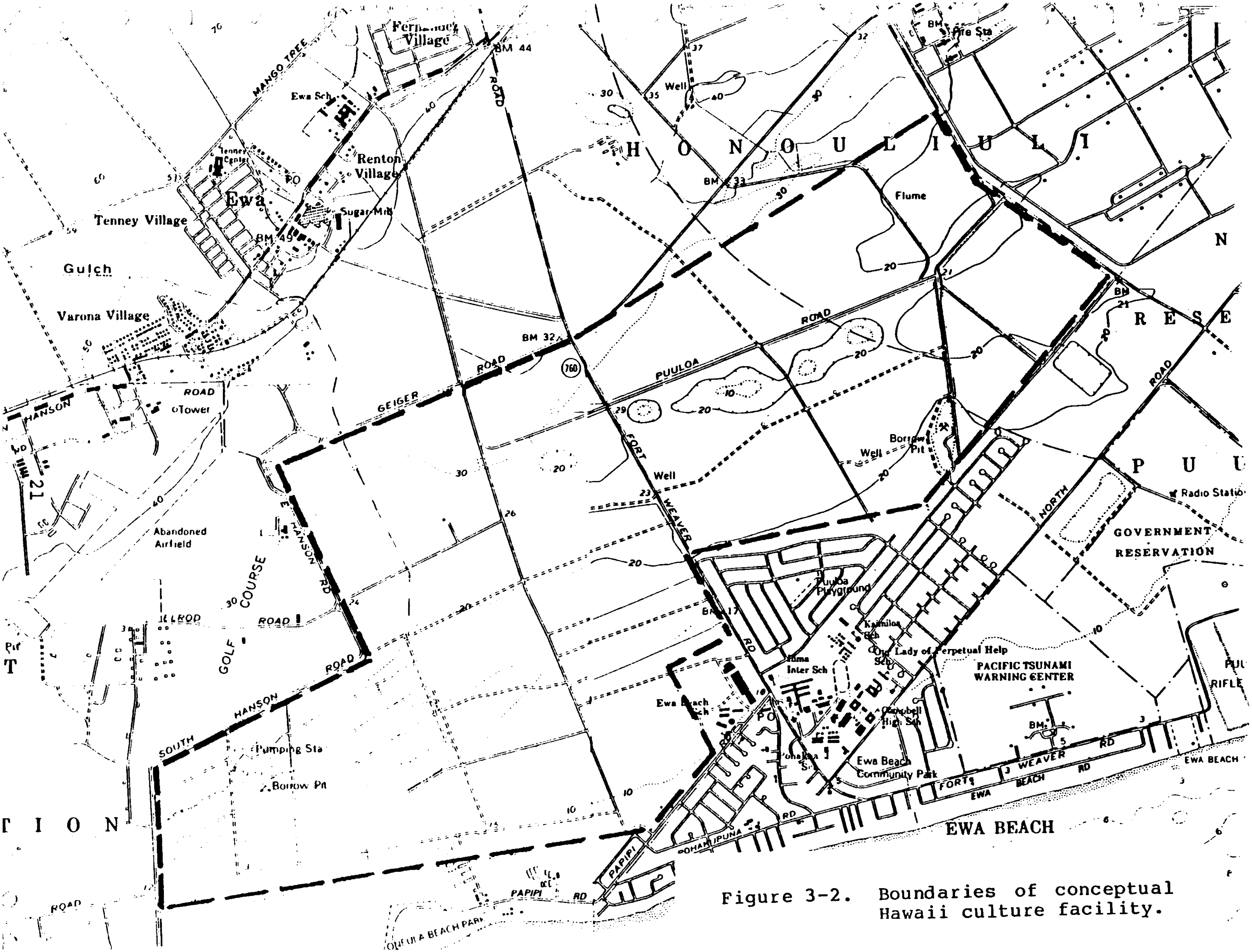
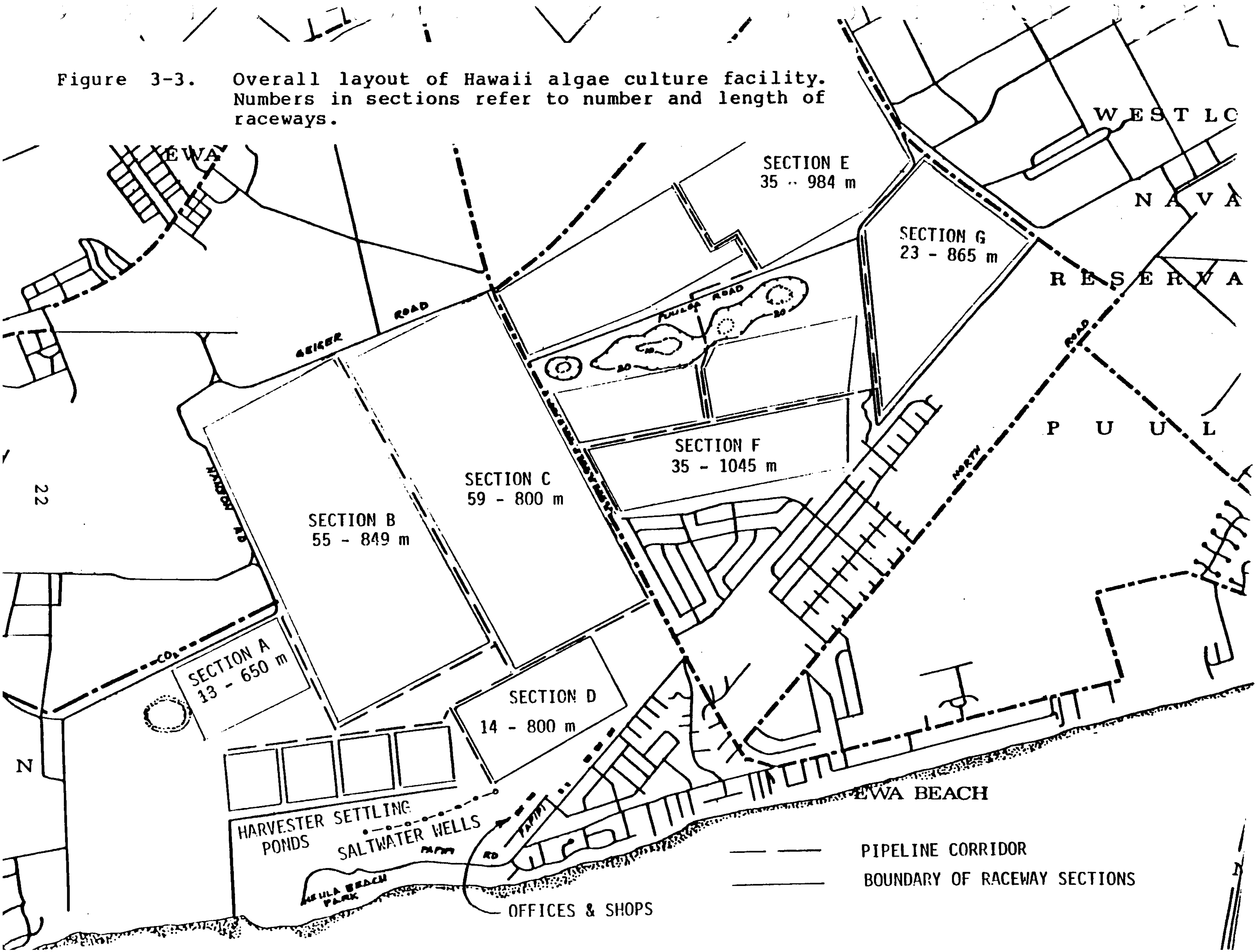


Figure 3-2. Boundaries of conceptual Hawaii culture facility.

Figure 3-3. Overall layout of Hawaii algae culture facility. Numbers in sections refer to number and length of raceways.



reported to have very good communication with the sea. The Honolulu-based well drilling company, Roscoe Moss, Inc., reported that there should be little difficulty in obtaining 35-40 million gallons per minute from seven or eight 100-foot deep by 20-inch diameter wells drilled in this area. Water is pumped from these wells through pipe corridors established between the production raceways (Figure 3-3). The facility harvesting system is also located as close as possible to the waterfront. This would enable a gravity feed, open channel flow system to transport the water with its suspended biomass from the raceways to the harvesters. This network of open channels runs parallel to the feed water pipes in the pipe corridor shown. Following removal of the biomass from the water, the effluent is discharged through another open channel leading directly to the ocean.

CO_2 is supplied by a pipeline that originates at the Hawaiian Independent Refinery, Inc. (HIRI), a subsidiary of Pacific Resources, Inc. (PRI). The refinery is located at Campbell Industrial Park, just west of the Barbers Point Naval Air Station. The refinery produces CO_2 as a byproduct of its oil refining and SNG production operations. Nearly pure (>98%) CO_2 would be purchased from HIRI and transported through a pipeline which traverses the Barbers Point Naval Air Station and then winds throughout the production facility, along the pipe corridors.

A separate set of pipes supplies non-carbon nutrients to the raceways. Nutrient mixing takes place near the seaward side of the facility because of its proximity to the water supply wells and the main buildings.

The raceways themselves are laid out approximately parallel to the elevation contours, and obvious physical landmarks such as large holes and borrow pits are avoided. All the facility offices, storehouses and employee space are located along Papipi Road just on the outskirts of Ewa Beach township. Major roadways such as Fort Weaver Road, Geiger Road and Puuloa Road would not be disturbed by the facility. Only temporary agricultural roads would be disturbed.

The facility has 234 raceways with a total effective culture area of 409 ha. Roads take up another 130 ha. Because of the irregularity of the site boundaries and the presence of areas unsuitable for raceway construction, another 143 ha are left open. Some of this area can be used for processing facilities and effluent utilization.

3.4 Raceway Description

The basic characteristics of the raceway designed for the Hawaii commercial facility are shown in Figure 3-4 and listed below:

1. The raceway channel width is 10 m and the depth is 12 cm.

2. Raceway length is variable from 650 to 1400 m depending on site topography and boundaries; 800 m is used for design purposes.

3. The raceway slope is 0.08%.

4. Raceway channels are constructed from earthen berms which are a minimum of 24 cm high over the first 900 running meters of the raceway. Over the last 700 meters these berms gradually increase in height to provide a water catchment area at the sump end of the raceway in the case of a pump failure or an electrical blackout.

5. The raceways are lined with 4" of lime-stabilized soil. The earthen berms are covered with 2" of lime-stabilized soil.

6. Mixing foils (10 cm square plates set at a 20° angle) are placed 20 cm on center with respect to the raceway width and 3 m on center with respect to the raceway length.

7. Water circulation is accomplished by pumping with a 720-rpm wet pit propeller pump located in a pumping sump at one end of the raceway.

8. Raceway water supply, nutrient supply, and harvest drain are all located at the same end of the raceway as the pumping sump.

9. CO_2 distribution sumps are constructed every 124 m along the running length of the raceway.

10. A 5 m wide graded earth roadway runs the full length of the raceway on either side.

The decision to include a sloped raceway system rather than flat raceways in the conceptual design was based both on the parametric study results and on a comparison of capital and operating costs for a flat versus a sloped raceway system. It has already been pointed out that a shallow raceway system like the one used at the University of Hawaii experimental facility will experience much higher head losses as the water moves along the channel than similar systems which run at slower velocities and deeper water depths. These high head losses are caused both by surface friction (60%) and the resistance of the mixing foils

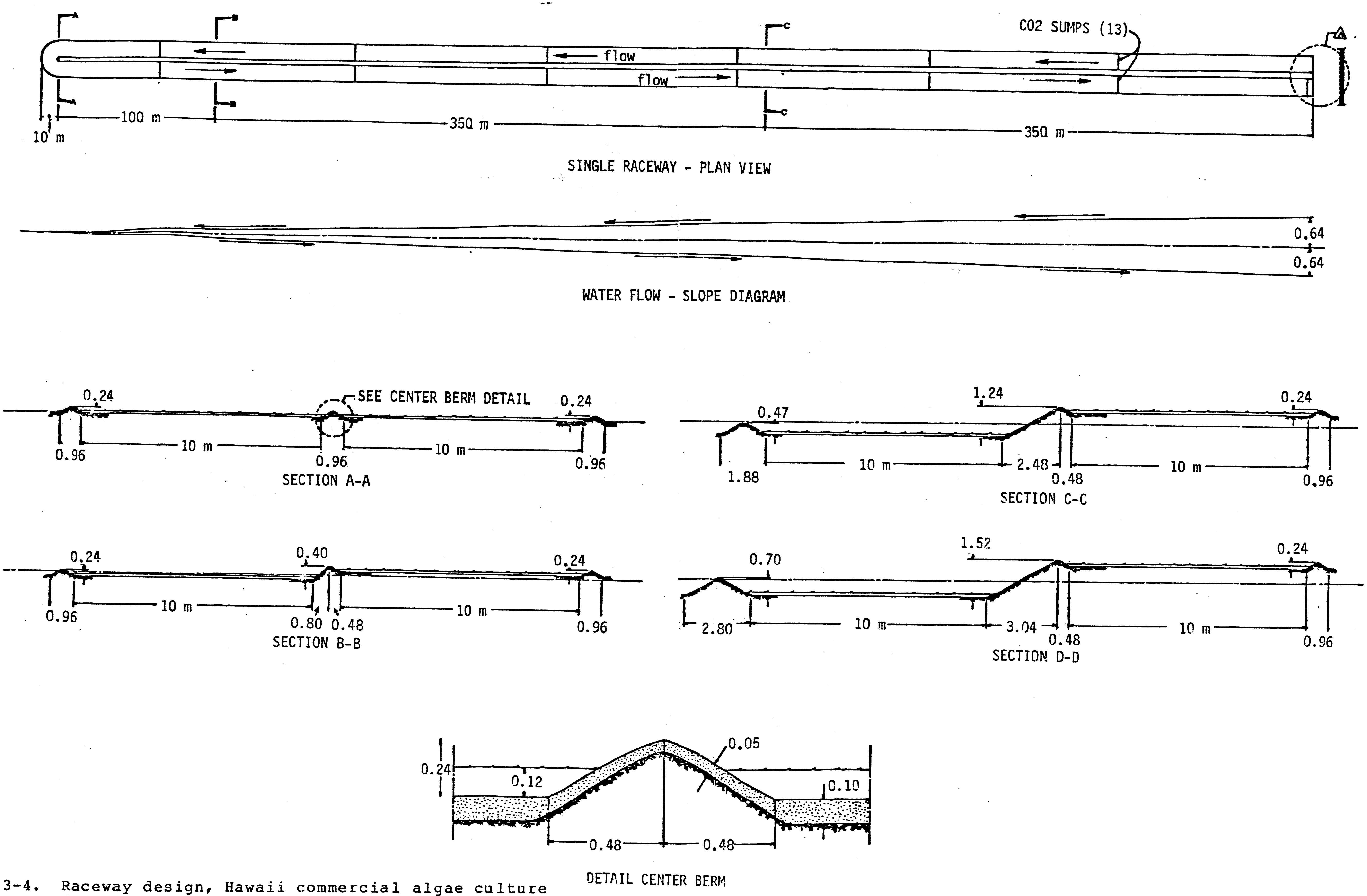


Figure 3-4. Raceway design, Hawaii commercial algae culture facility.

(40%). A paddlewheel in a flat raceway moves water by lifting it from a lower elevation on its upstream side to a higher elevation on its downstream side. Water is "piled up" and allowed to flow down to the next paddlewheel under the force of the "hill of water" behind it. The water depth and volumetric velocity are not continuous from one paddlewheel to the next, although the flow rate is continuous. If paddlewheels in a raceway are spaced far apart and head losses are high, the change in water depth and velocity as the water moves from one paddlewheel to the next will be very significant. The Hawaii raceway experiments indicate that only a 4 cm (8-12 cm deep) change in water depth can be tolerated without lowering algal production rates (E. Laws, pers. comm.). Therefore, given an 8 cm head loss per 100 meters of raceway length, it would be necessary to place a paddlewheel once every 50 meters in a commercial production facility modeled after the UH experiment. The paddlewheels would raise the cost of a flat raceway facility well beyond the cost of a sloped raceway facility despite the higher initial costs of the sloped raceways because of their greater earth moving requirements. Table 3-1 compares costs for construction and operation of a flat versus a sloped raceway system. Based on MOE estimates, the installation cost of 32 paddlewheels in a 1600 meter running length system would far surpass the relatively small $9000 cost differential due to increased earthwork costs associated with a sloped system and the small power savings ($2/raceway-day) potentially available from a nighttime flow reduction in a flat raceway system. The higher maintenance requirements of 32 paddlewheels versus one propeller pump and the greater difficulties in designing an automated cleaning system for the raceways due to interference by the paddlewheels are important operating cost factors favoring a sloped system.

The most important cost consideration in the construction of the raceway has already been identified as the raceway liner. Because of its importance a study was conducted of potentially acceptable liner types. Table 3-2 compares material costs, installation costs, expected life and other characteristics of the lining materials considered. Rammed earth or bentonite-lined raceways were not considered in this study. It was felt that such lining techniques would not be practical in a system where frequent cleaning and occasional draining of the raceway would damage the lined surface. Cost quotations are from the manufacturers of the various liners. Many of these costs may be optimistic. For example, the Hawaii State Soil Conservation Service reported that their costs to purchase and install large reservoirs lined with Hypalon ran as high as $1.50/sq. ft. (J. Lum, pers. comm.). This is more than double the price quoted in Table 3-2. Actual costs for installation of a lining system will be highly dependent upon the site and the specifics of the construction. Table 3-2 costs probably reflect the lowest prices for which a manufacturer believes his lining system could be installed. The least expensive liner is a 4" soil cement liner material.

CAPITAL COST ITEM	APPROXIMATE COSTS*	
	Flat with Paddlewheel	Sloped with Propeller Pump
1. Land Preparation	$10,000	$10,000
2. Surveying	400	500
3. Cut & Fill for Berms/Slopes	2,000	11,000
4. Rough Grade	1,500	1,500
5. Laser Level	4,000	4,000
6. Liner (soil cement)	42,000	42,000
7. Pumps & sumps	32 @ 5,000 to 20,000 ea	1 @ 25,000 ea
8. Mixing Foils	55,000	55,000
9. Total	274,900 - 754,900	149,000
OPERATING COST CONSIDERATIONS		
1. Pump Efficiency	0.65 max	0.80 max
2. Power Costs **		
Daytime	64 KWH/rcwy/day	52 KWH/rcwy/day
Nighttime	19.2 KWH/rcwy/day	52 KWH/rcwy/day
Total ($0.11/KWH)	$9.15/day	$11.44/day
3. Maintenance (Pumps & Paddlewheels)	32 @ $500 to $100 ea/yr	1 @ $300/yr
4. Est. Cleaning Time (min/day)***	60	30

* Based on 1 raceway, 1600 m running length, 10 m wide, 12 cm water depth, clay soil.

** Daytime Velocity both raceway types = 30 cm/sec
Nighttime velocity sloped = 30 cm/sec; flat = 20 cm/sec

*** Involves lifting cleaner over paddlewheels plus occasional paddlewheel cleaning

Table 3-1. Cost comparison for construction and operation of flat (with paddlewheel) vs. sloped (with propeller pumps) shallow raceways.

LINER TYPE	MT'L COST PER SQ FT	INSTALLATN PER SQ FT	LIFE (YRS)	COMMENTS
CONCRETE 2" @68.30/cy	$.40	$.40-.60	25	
SOIL CEMENT, 4"	.07	.09 (nu)	25	
MEMBRANE LINERS				
PVC Non-reinf.(30mil)	~.20	.10-.15 (nu)		Not recommended, cannot be left exposed
CPEA Non-reinf(30mil)	.30	.10-.15 (nu)	20 G	Poor tear strength
HDPE (60 mil)	.30	.30	20	
Hypalon (Reinf)(36mil)	~.50	.10-.15 (nu)	20 G	Only sold reinforced
CHEMICAL LINERS				
Chevron Ind. Membrane	1.02	.10 (nu)	5 G	Cracking problems

(nu) = non-union
G = Guaranteed

Table 3-2. Comparison of potential raceway liner materials.

Soil cement or lime stabilization of soil is a process of mixing cement or lime with the existing soil to form a concrete-like surface. The decision to use cement or lime for stabilizing soil is based on the type of soil to be stabilized: sandy soils are best stabilized with cement while clay and silty soils are more economically stabilized with lime. A combination of lime and cement may be necessary for the Hawaii-based facility; this decision would best be made by a qualified soil engineer prior to construction. The process of stabilizing a raceway would be as follows:

could have made preliminary estimate

1. Raceway earthmoving operations are completed and fine grading is carried out.

2. A layer of soil of the same thickness as the desired soil stabilized surface is overturned using rotary tiller equipment.

3. The dry cement or quick lime is spread in the proper ratio over the loose soil.

4. The rotary tiller equipment is again used to mix the cement/lime with the soil as thoroughly as possible.

5. A carefully measured volume of water is applied to the soil-cement mixture and mixing is continued.

6. The mixture is compacted to maximum density using heavy steel wheel, sheep's foot and rubber tire rollers.

7. The surface is fine-graded (laser leveled).

8. The surface is covered with straw or some other material that will help maintain the moisture content of the soil cement and lead to adequate curing or cement hydration.

It should be noted that soil cement is also often applied by removing the surface layer of soil and bringing it to a central mixing plant to be mixed with cement and water. Because of the better mixing achieved by this process it is often possible to reduce the amount of cement or lime necessary to stabilize the soil.

The layer of soil cement proposed as a liner for the Hawaii based facility would be 4" thick on the raceway bottom surfaces and 2" thick on the sloped berm surfaces. For inexpensive upkeep and maintenance of this liner material a polymer soil stabilizer such as Parabond could be used to repair cracks or areas where the soil cement was inadequate to prevent water percolation.

3.4.1 Raceway Dimensions

The 10-meter raceway width was selected based on several considerations. From the parametric study of raceway hydraulics it was discovered that head losses could be reduced if raceway width was at least 30 times the raceway depth, setting a lower limit of 3 m width on the raceways. An upper limit for raceway width is more difficult to define. As width increases, the cost of CO sump installations and pumping sump installations will increase. It will also become more difficult to lift equipment and replacement supplies to the center of the raceway. However, neither of these reasons would necessarily limit the raceway to the 10 m width which was selected for this study. Some commercial algae culture raceways are approximately 10 m wide, so this width seems to be operationally manageable.

A rationale for selecting raceway length was also difficult to define. From the parametric study it is known that total head loss over the running length of the raceway is proportional to the length. Therefore, for a 1600m running length raceway the total head loss is 1.28 m while for a 2000 m running length raceway the head loss is 1.6 m. A tradeoff develops between the costs incurred in digging a sloped raceway to these greater depths versus the saving accrued by having fewer, longer raceways (fewer pumps, fewer pumping sumps). A further consideration relative to length is the percent of the total biomass production which is assigned to a single raceway. For a 1600 m running length raceway which is 10 meters wide, 4% of the total production of a 1000 acre facility is located in one raceway, and could be lost if the raceway culture "crashes" or a breakdown occurs. Raceway length may become an economic question: how much production loss can be tolerated with a single raceway crash? For the Hawaii production facility raceway nominal length was set at 800 m (1600 running meters) but raceways of varying lengths from 650 m to approximately 1400 m are included in the facility design in order to use the available land most efficiently.

3.4.2 Mixing Foil Design

Second only in importance to lining materials with respect to overall facility costs is the cost of the mixing foils. The means by which the mixing foils increase production in the Hawaii experimental facility is not totally understood. The foils cause vortices which apparently expose the algal cells to alternating light and dark periods. Recent experiments at SERI suggest that light modulation of sufficient frequency enhances photosynthetic efficiency because the cells respond to the average light intensity received instead of the maximum flash intensity (Terry, 1985). However, the relationship between production and foil spacing, shape, and position in the water column is not understood. The foil sections also have an impact on raceway cleaning methods and liner selection. In the UH experimental production facility, raceway cleaning is carried out by hand on a daily basis. Cleaning consists of scraping a brush across all of the raceway walls and bottom surfaces to remove any algae that has attached itself to these surfaces. Mixing foils present little interference in this cleaning process since it is carried out by hand in the experimental system. In a commercial scale facility with 10 m wide raceways, the cleaning process will have to be mechanized. The presence of mixing foils in the raceway will be a considerable obstacle to, for example, a street sweeper-type cleaning machine driving down the middle of the raceways. A raceway cleaning method and foil design must go hand in hand. Similarly, the raceway lining material will impose limitations on the foil design. Selection of an impermeable membrane liner would preclude the use of foils that are supported by vertical rods driven directly into the raceway bottom surface. The large number of holes in the lining material produced by such a foil design would no doubt lead to major leakage problems. Foil design, cleaning machine design, and liner selection must therefore all be considered together. another reason to avoid liners

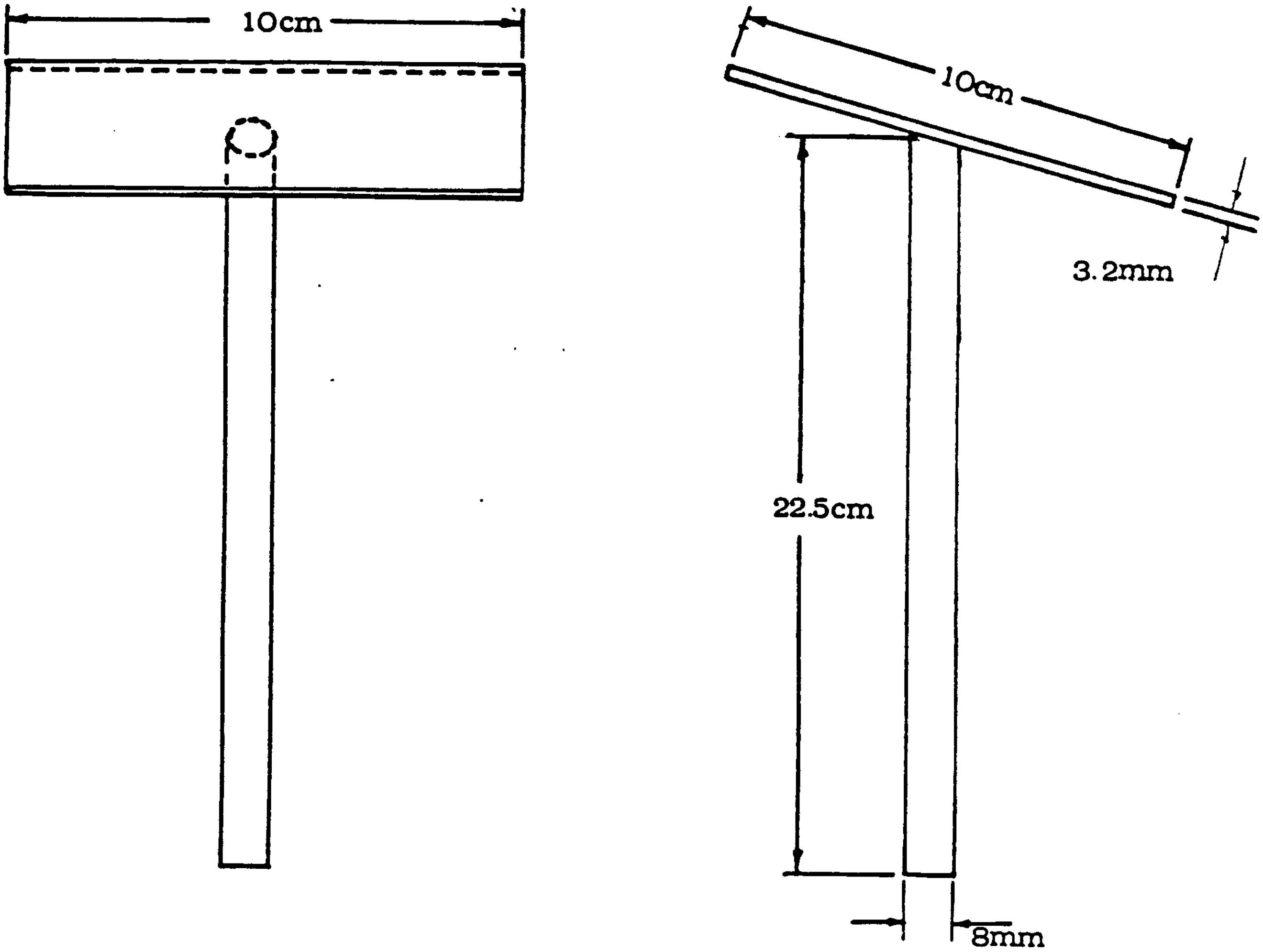
The selection of a soil cement raceway lining material puts very few restrictions on the mixing foil design. One mixing foil design that was considered was an array of foils supported by a strut-like structure from above that could be swung out of the water column during cleaning operations. A second configuration was a more permanent foil installation in which foils were either glued or driven into the soil cement surface. The latter configuration was considered superior because of its simplicity and lower maintenance costs. The recommended foil design is shown in Figure 3-5. The foils are constructed from #5086 aluminum alloy which is resistant to saltwater corrosion. They are permanently fixed in the raceway by drilling holes in the soil cement raceway surface and grouting the vertical support member into place.

3.4.3 Cleaning Machine Design

A cleaning machine which can span the width of the raceway is required that is compatible with the foil design (see Figure 3-6). A cleaning machine with a very large diameter, soft brush similar to those used in car washes is envisioned. The machine moves down the raceway; the brush slowly rotates and cleans the raceway surfaces, passing directly over the permanently installed foil sections without damaging them. Considerable design and development work would be required to construct such a cleaning machine.

3.4.4 Raceway Pump and Pumping Sump

The last detail to be discussed under the raceway description is the pumping sump located at one end of the raceway. A 16-inch diameter, 720-rpm wet pit propeller pump is mounted vertically at the extreme end of this pumping sump and moves water through a pipeline to the higher elevation adjacent raceway (Figures 3-7 and 3-8). The sump depth was determined by



NOT TO SCALE

Figure 3-5. Design of individual mixing foil for algal raceways.

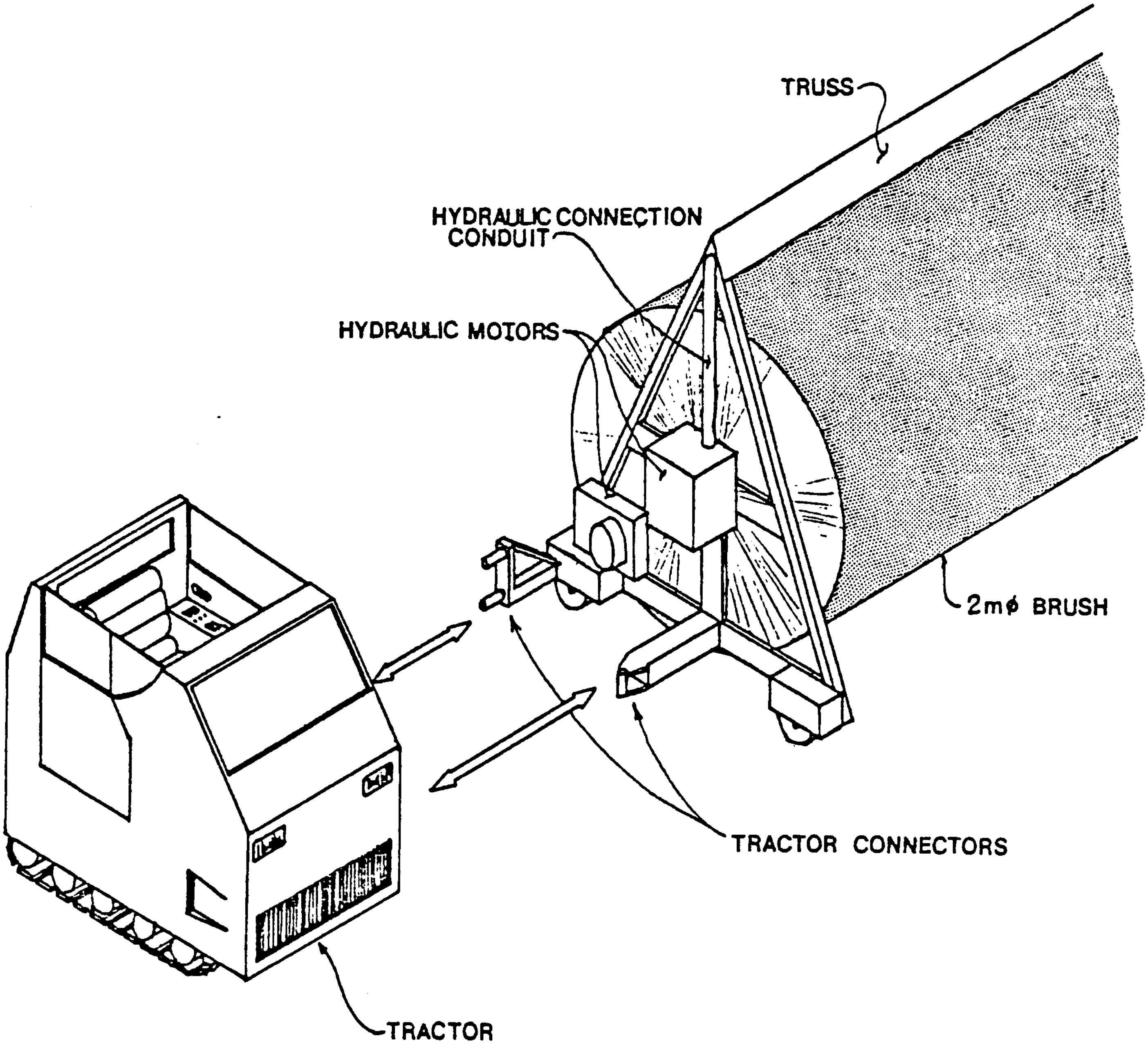


Figure 3-6. Cleaning machine concept for shallow algal raceways.

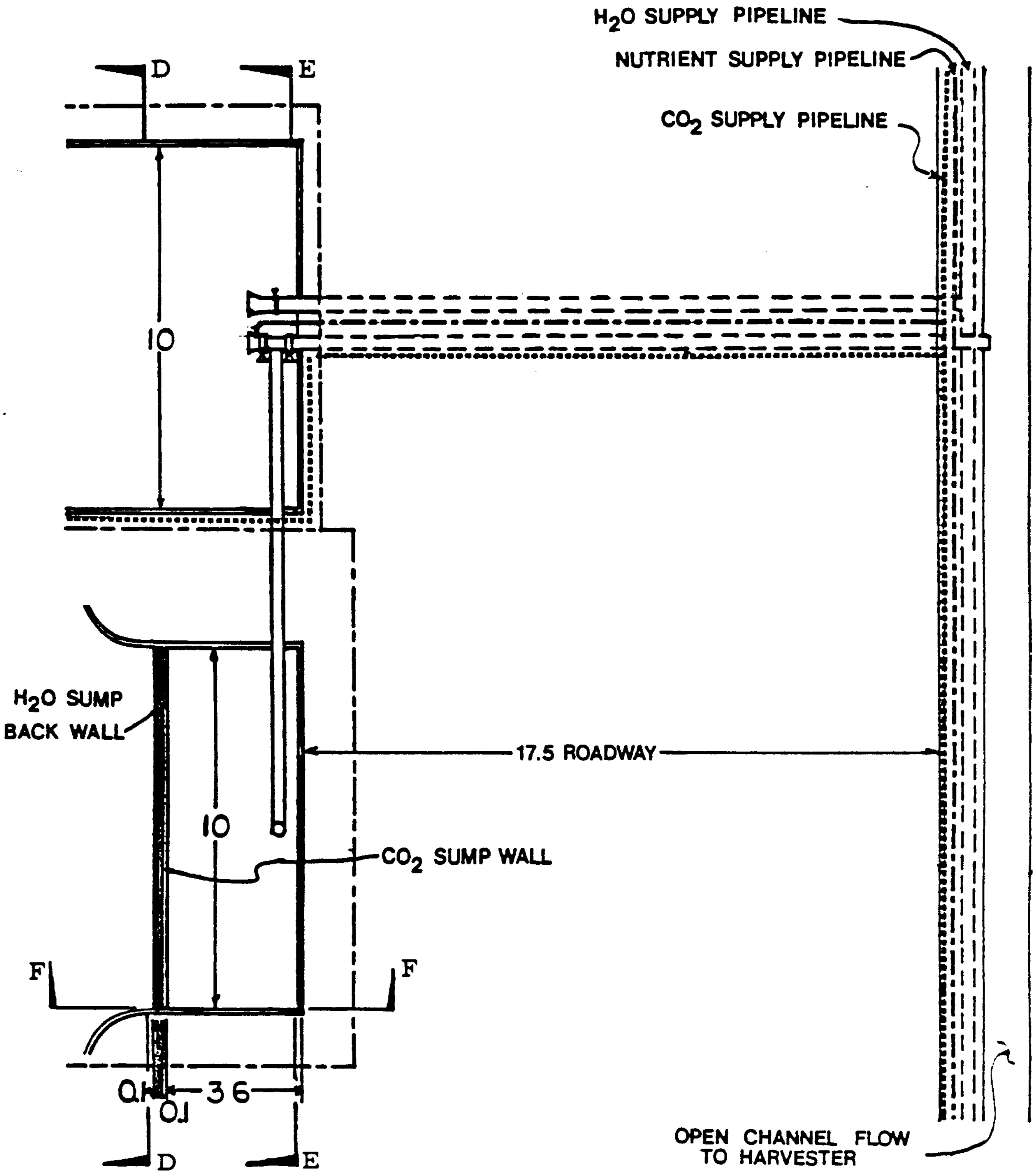


Figure 3-7. Overhead view of sump end of raceway showing pump, supply pipes, and harvest channel. Dimensions are in meters.

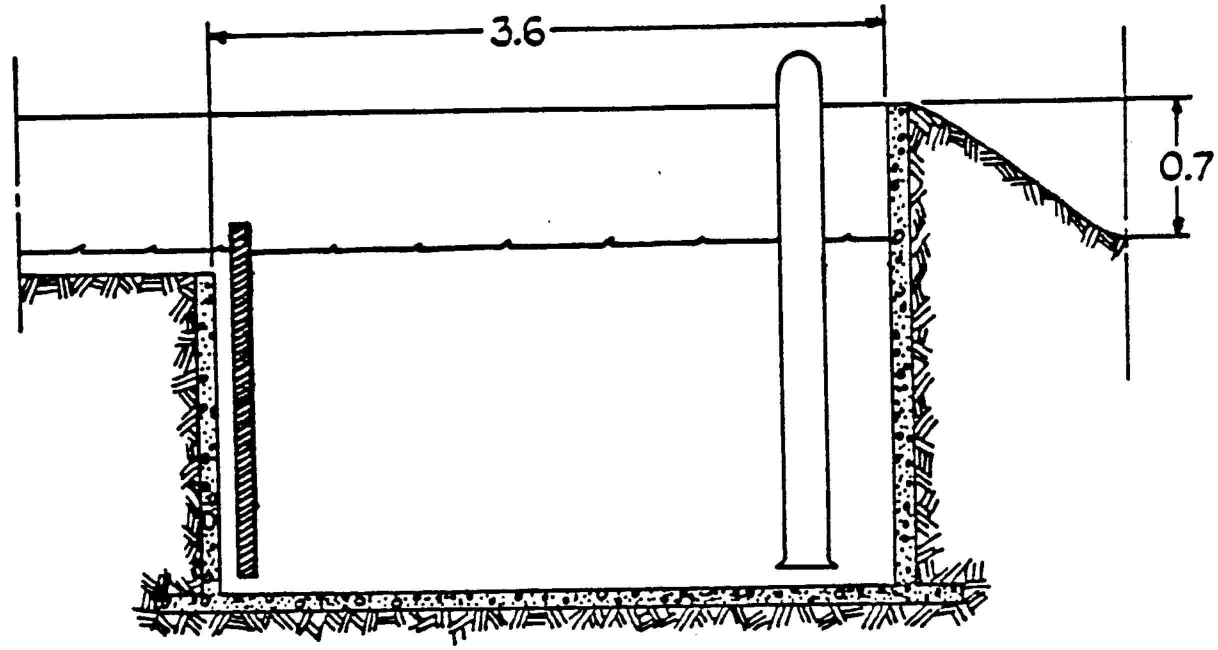


Figure 3-8. Cutaway side view of raceway pump sump. Dimensions are in meters.

the required positive suction head for such a propeller pump. The sump is constructed of concrete rather than soil cement (which would have to be sloped) to save space.

A propeller pump was chosen rather than the airlift pump presently used in the UH experimental raceway because of the greater efficiency of propeller pumps. Computer simulations of a 16-inch diameter, 720-rpm wet pit propeller pump indicate that 84% efficiency can be achieved at 25 off normal pitch angle (M. Boudet, M & W Pump Corporation, Deerfield Beach, Florida). The efficiency of an airlift pump depends on flow rate, pipe size, air-to-water ratio, and submergence depth of the airlift (Wheaton, 1977). It is unlikely that a practical airlift pump can be built for the raceways that would exceed 50% efficiency; such an efficiency would probably require a deeper and more expensive pump sump than required for a propeller pump. Airlift efficiencies of 30% have been cited for algal raceway applications (Hill et al., 1984). The economic analysis reported later in this document indicates that the lower efficiency of airlifts would increase the cost of algae produced by the conceptual facility somewhat unless the airlift pumps cost substantially less than propeller pumps.

One task proposed for future experimentation is proof of the utility of low-rpm propeller pumps versus airlift pumps in raceway culture of *Platymonas*. Centrifugal pumps are reputed to damage some microalgae in culture, but the low-rpm, low-head pump type proposed here should not expose the algae to extreme stress. Early in the series of experiments at the UH facility, *Phaeodactylum tricornutum* was cultured as successfully with a centrifugal pump as with an airlift (M. Chalup, Hawaii Institute of Marine Biology, pers. comm.). Inhibition of photosynthesis by oxygen supersaturation has been suggested as a limit on algal production in some systems (Hill et al., 1984), and use of an airlift may reduce oxygen supersaturation. On the other hand, airlift pumps may encourage increased outgassing of CO_2.

3.5 Facility Seed Raceways

A number of smaller raceways will be required to produce starter stock to seed the full-sized raceways. These small raceways will be essentially scaled-down replicas of the full-sized raceways just described. They will be located near the main operations buildings since their management will probably be more labor-intensive than the full-sized system, and because they will probably be used for stock improvement experiments when they are not needed for start-up purposes. Included in this construction will be four 1 m x 16 m long raceways (32 m running length), four 5m x 25m raceways (50 m running length) and four 10m x 100m raceways (200 m running length). The operation of these raceways is described under Facility Operation (Section 4.1).

3.6 Water Supply System

To transport the water from the saltwater wells to the raceways located at various elevations throughout the facility, several pipelines run through a pipe corridor that winds between the raceways throughout the facility. A single well and pump installation are dedicated to supplying water to the raceways at elevations greater than 10 m above sea level. The water in these raceways amounts to approximately 10% of the total water volume in the facility. The largest number of raceways are located between 6 m and 10 m elevation; four pumps and a pipeline service these raceways, which make up approximately 66% of the total water volume of the facility. A pair of pumps and a pipeline supply the raceways which are closest to the ocean and between an elevation of 3 m and 6 m above sea level. These raceways make up the remaining 24% of the water volume of the facility. All pipes are low pressure pipelines, allowing the use of PVC irrigation pipe. Valves are located every 1/2 mile along each pipeline so that a section of pipeline can be isolated for repairs. Calculation of maximum pumping heads and maximum flow rates to each of the elevations within the facility are shown in Appendix 4.

Water is delivered from the unburied feeder pipelines to the raceways through a buried PVC line which runs under a roadway between the pipe corridor and the raceway sump end. A valve in series with this branch line can be activated when refilling a particular raceway. The valves could be hand-operated, or they could be remotely activated from a central controller to permit automatic harvest and filling of the raceways on a set schedule. The branch pipelines are buried to a depth of 1.2 m to protect them from the load of heavy vehicle transportation over the feeder roads throughout the facility.

Water obtained from wells near the ocean on Oahu is generally less saline than seawater. Water of less than 35 ppt salinity is desirable because evaporation in the raceways will raise the salinity in the raceways to an equilibrium level about 5 ppt higher than in the input water. From the experience of AAI and other aquaculture producers in Hawaii, a source water salinity of 25-30 ppt is likely; the equilibrium salinity will then be 30-35 ppt, which should be adequate for *Platymonas* (SERI Biomass Program Monthly Report, November 1984).

H_2O Salinity ✓

3.7 Carbon Dioxide Supply

Figure 3-9 illustrates the path of the CO_2 supply pipeline from Hawaiian Independent Refinery to the culture facility. The running length of the pipeline is approximately 7700 m. The daytime flow rate through the pipeline is approximately 14,600 standard cubic feet (SCF) per minute. The CO_2 supplied by the refinery would be scrubbed from the flue gas produced by the refinery process and would exceed 98% purity (R. Fujita, PRI, pers. comm.). The pipeline itself is a low pressure pipeline

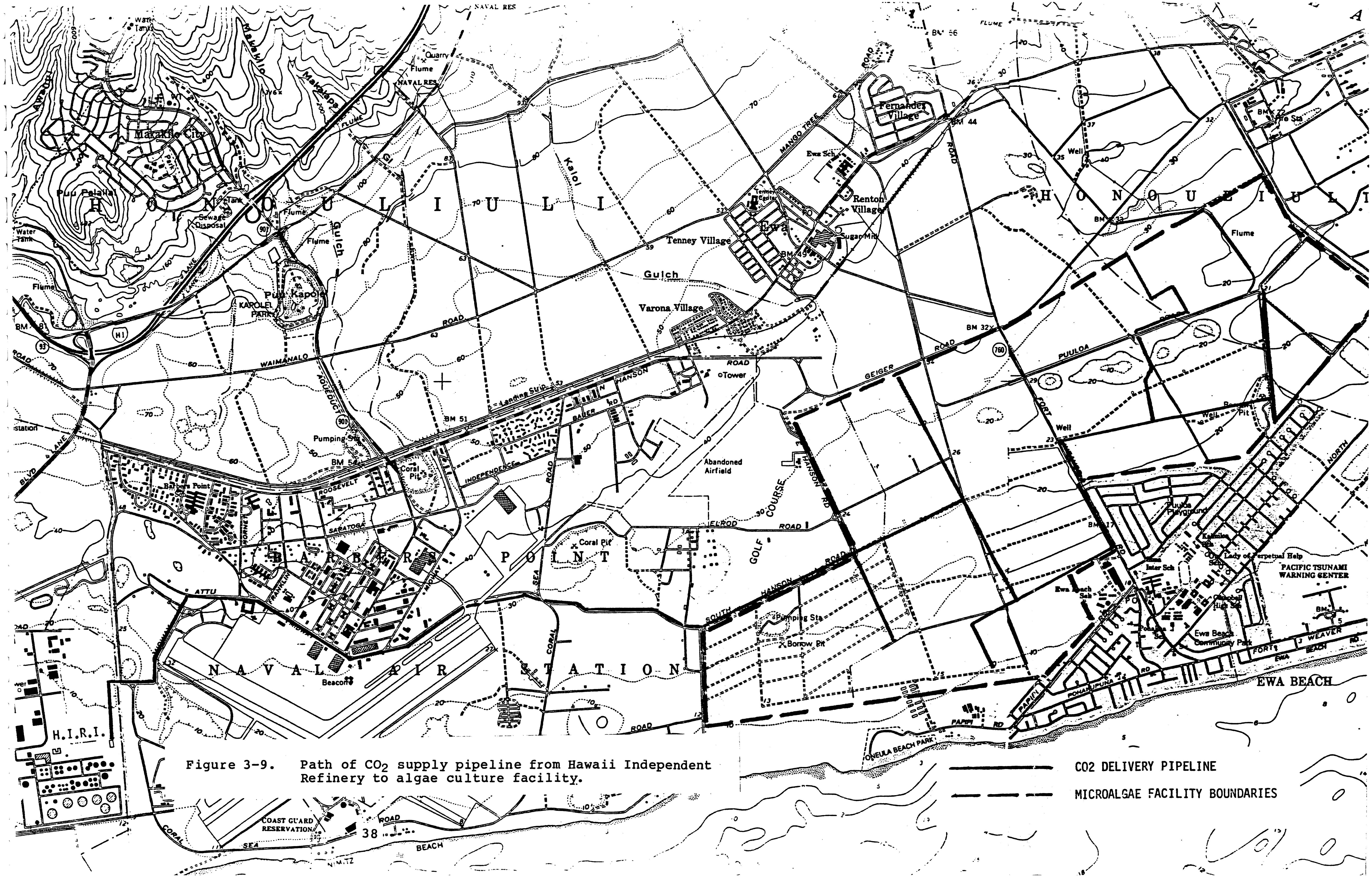


Figure 3-9. Path of CO_2 supply pipeline from Hawaii Independent Refinery to algae culture facility.

124 g/m²-d highest prod. rate

buried along the roadways running through the Barbers' Point Naval Air Station. Fifteen 1000 SCFM blowers delivering 10 psi will be required to push the CO_2 from the refinery to the Ewa Beach facility and to distribute it to the raceways through the facility feeder lines.

U-tube sumps distribute the CO_2 within the individual raceways. Figure 3-10 illustrates a side view of a such a sump. A sump is located every 124 m along the running length of the raceway. This distance was calculated based on the assumption that CO_2 uptake is directly proportional to phytoplankton growth rate. The highest known production rate is 124 g/m^2-day, based on growth rate extremes reported by Laws (1984). Such a high production rate would probably occur only occasionally on the third day of the growth cycle in a raceway. It was also assumed that the CO_2 concentration in the water could be raised from 25% of saturation to 75% of saturation at each sump. For further details on the operation procedures for these CO_2 sumps, see Facilities Operation.

The optimum design of the CO_2 sump remains a a major unknown in the facility design. CO_2 costs will be a major expenditure in the facility operation, so a design to maximize the uptake efficiency of CO_2 is required. The U-tube type diffuser shown in Figure 3-10 increases the concentration of CO_2 in the water through two mechanisms. Because the water is moving at a downward velocity faster than the gas bubbles are rising, the gas-water contact time is increased through the U-tube and the absorption of CO_2 is increased. In addition, the saturation concentration of CO_2 is increased as the water descends into the U-tube because of the hydrostatic pressure increase; in a properly designed system, the water emerging from the U-tube could actually be supersaturated because of this pressure increase. The rate of CO_2 absorption through the U-tube is a function of the CO_2-to-water volume ratio through the U-tube, the dissolved CO_2 concentration going into the U-tube, the U-tube depth and the CO_2 bubble size. For the purposes of this study it was assumed that the concentration of CO_2 in the water has dropped to 25% of total saturation at the entrance to the U-tube. At the exit of the U-tube it was assumed that the concentration in the water would equal 75% of total saturation. The depth of the CO_2 sump required to achieve this increase in CO_2 concentration is unknown. Tests should be conducted to determine the optimum depth of this CO_2 sump to maximize CO_2 absorption without creating excessive head loss through the sump. uptake rate ? efficiency

The CO_2 sump itself is precast from concrete. The center wall that forms the U-tube structure is also reinforced concrete. (A center wall of some lighter material like fiberglass-reinforced wood could also be used and might allow removal of the wall for cleaning and repair of the sump.) A 3" PVC pipe transports CO_2 from the feeder line in the pipe corridor down the center berm of the raceway with branch lines going to each CO_2 sump. Remotely controlled electric solenoid valves control the flow of CO_2 to each sump. A pH probe with preamplifier in each raceway monitors

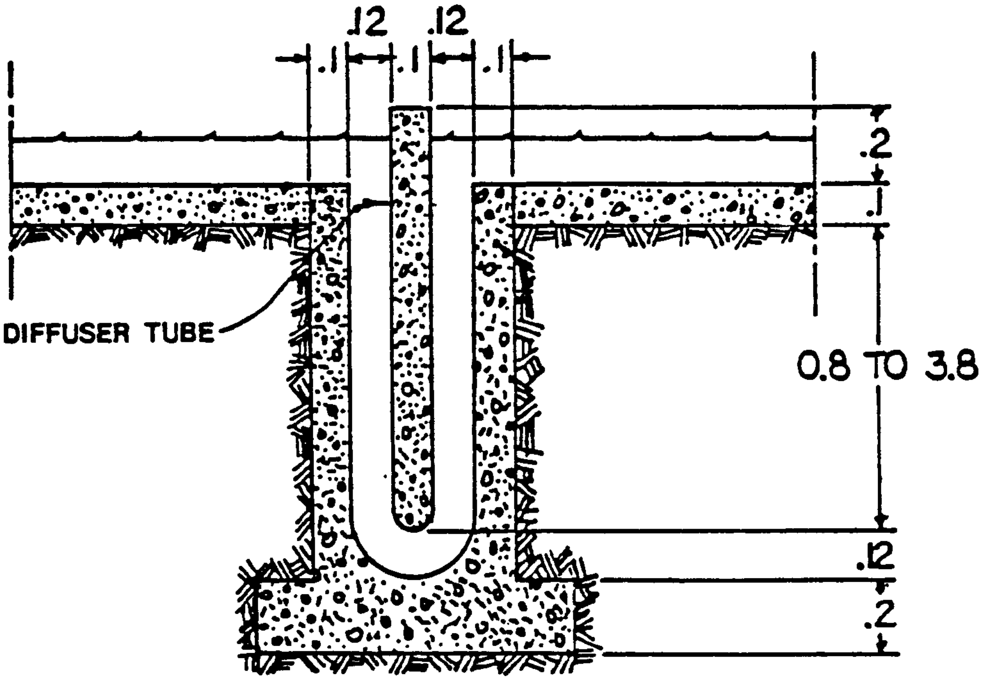


Figure 3-10. Cutaway side view of CO_2 sump. Dimensions are in meters.

carbon uptake. CO_2 is sparged into the water column through Plastipor diffuser tubing, which can emit bubbles smaller than 1 mm in diameter (M. Mulvihill, Aquaculture Research/Environmental Associates, Homestead, Florida, pers. comm.).

3.8 Non-Carbon Nutrient Supply

Algal nitrogen requirements are supplied by anhydrous ammonia, and phosphate requirements are supplied by a liquid fertilizer with an analysis of 10-34-0. The ammonia and 10-34-0 are dissolved in water such that the ammonia concentration is 10% by weight and the 10-34-0 concentration is 3.6% by weight. A chelated trace metal mix is also supplied.

The nutrient solution is pumped in a separate pipeline throughout the facility during the daylight hours. The volumetric flow rate in this pipeline will be much lower than in the water pipelines previously described, and only a very small pump will be required. A 3" PVC pipe is laid unburied throughout the pipe corridor in the facility. Branch lines from this feeder pipeline to each individual raceway are buried in the same trench as the water supply pipeline, and flow rates to each raceway are controlled and monitored by a multi-position, remotely controlled valve and a flow meter, based on algal growth as measured by carbon uptake.

Raw nutrients are transported by sea from Western Farm Services in California to Hawaii. The anhydrous ammonia and 10-34-0 are shipped in Department of Transportation-approved containers which are 12' in length and 4' in diameter. The ammonia is a compressed and liquefied gas at approximately 250 psig, and the Hawaii commercial facility would require up to 8 ammonia tanks (approx. 2.5 MT each) to satisfy its daily nitrogen requirements. The 10-34-0 fertilizer arrives in similarly sized tanks, but only two would be required per day to provide for the facility's needs. The nutrient tanks are shipped by barge every three months. A 54,000 sq. ft. area (0.5 ha) is required to store the nutrient tanks. Flatbed trucks each carrying eight tanks per load ferry the cargo from the port of Honolulu to the Ewa Beach facility and stockpile the empty tanks at the port shipyard for the return voyage.

3.9 Harvesting and Harvesting Supply System

Harvested culture water flows to the settling ponds through a network of open channels constructed in the pipeline corridor that winds throughout the facility. The use of an open channel system instead of large diameter piping facilitates use of a gravity flow system and saves on pumps and power costs. The channels are rectangular in cross section, with the channel water depth equal to one-half the channel width. Channel sections are individually sized based on the maximum flow of water each will be required to carry and on the local ground slope available in settling ponds

each section of the installation. Water is transported to the harvester installation located close to the ocean front as shown in Figure 3-3.

The settling ponds proposed for the commercial facility are based on a very large extrapolation of the previously described harvest experiments. Four settling ponds, each 286 meters square surrounded by a 2-1/2 m high earthen berm with a 2:1 slope are envisioned. Each settling pond has a 5 m wide pumping sump with 3 propeller pumps used to lift water from the harvesting supply channels into the settling pond. The bottom of a settling pond is divided into 10 equally spaced sections, each of which is separated from the next by a buried 20" PVC pipeline. The settling pond is lined with 6" of lime-stabilized soil or soil cement and the inner berm walls are lined with a 3" soil cement surface. Running parallel to the buried pipelines and secured to the soil cement surface are aluminum angle iron sections which help prevent runoff of the settled biomass from the bottom of the settling pond when it is drained. Water is drained from the settling pond through the buried pipelines and flows into the effluent channel which is located on the ocean side of the settling pond installation. Wet vacuum pumps mounted on trucks equipped with large storage tanks are used to remove the settled biomass from the bottom of the drained pond. A more detailed explanation of the operation of the settling pond is given in the Facility Operation section of this report.

3.10 Effluent Disposal System

Effluent from the harvester installation runs through channels and flows into the sea. A 2.4 m wide open channel is required for effluent disposal, given the high volume flow rates with which the settling ponds will be drained. Special permits and variances will be required to obtain State and Federal permission to release effluent directly into the ocean. However, Marine Culture Enterprises, a large intensive shrimp farm in Kahuku, Oahu, recently established a precedent in obtaining permission to channel a similar daily volume of aquaculture effluent directly into the sea. It is assumed that similar permission could be acquired for a commercial microalgae facility on Oahu. The required regulatory procedures would probably take 6-12 months; costs to prepare environmental assessments would probably be $25-50,000. The $50,000 cost figure is used in the economic model. all or nothing proposition

3.11 Building and Storage Facilities

As previously described, office buildings, storage facilities, warehouses, labs, shops and employee space will all be located adjacent to Ewa Beach township along Papipi Road. It is assumed that two office buildings, each of approximately 2000 sq. ft. would be the minimum requirements for such a facility. Storage facilities are provided as large prefabricated metal warehouse structures; 10,000 sq. ft. should be adequate. These warehouses store supplementary chemicals and nutrients not included in the phosphorus and nitrogen supply earlier mentioned, as well as spare parts, stockpiled construction supplies, cleaning supplies and equipment used in the day-to-day operation of the facility. Another 10,000 sq. ft. is housed in similar structures and used for shop space and laboratory space. Given the large amount of moving equipment involved in such a facility, a well-tooled garage for performing all types of repairs and overhauls on moving equipment would be included in this shop space as well as a variety of machine shop tools, lift cranes and space to perform a variety of plumbing repairs. The laboratory space includes a large culture room for seedstock maintenance and improvement. It also contains analytical equipment and probably the computer (with backup and non-interruptible power supply) that monitors and controls water and nutrient distribution throughout the farm. An employee building of 8000 sq. ft. is also assumed necessary to provide showers, cafeteria, conference rooms and restroom facilities for the employees. The employee building could also be a prefabricated metal structure.

3.12 Miscellaneous Equipment Requirements

The support activities associated with the day-to-day operation of the facility will require different types of moving equipment. At least two hydraulic cranes will be needed to perform lifting duties involved with pump installation and cleaning machine maintenance. A minimum of four 4-ton fork lifts would be required for unloading supplies and light lifting duties. To speed transportation around the facility, 20 utility vehicles which resemble gasoline powered golf carts are considered necessary. These would be used by the staff monitoring the day-to-day operations of the facility, by workers involved in cleaning the CO_2 and water sumps and by maintenance crews. Heavy transportation needs will be supplied by five light trucks, four heavier trucks and a pair of flatbed trucks. The flatbeds would be used primarily to transport nutrient tanks to and from the Honolulu shipyard. Five portable, hydraulically driven, large-diameter propeller pumps would also be required by the facility to provide for emergency pumping requirements during breakdown and repair of the raceway circulating pumps or harvesting pond lifting pumps.

4.0 FACILITY OPERATION

startup Time 15 days -
relates to covarient failu

4.1 Start-up

The office/laboratory facilities will include a culture room to maintain cultures of Platymonas. Cultures will be maintained in flasks and 20-liter carboys in standard media. They will be used for initial facility start-up and to restart the facility in case of catastrophic culture failure. The 20-liter carboys will be used to "seed" several 400-liter indoor vats which in turn can be used as the source of algal stock for the outdoor raceways.

To start up the facility, vat cultures will be transferred to a series of outdoor raceways, similar to but smaller than production raceways. As the cultures grow, they are transferred to larger raceways until sufficient culture volume is produced to stock production modules. The start-up raceways are sized to accommodate the ability of Platymonas to increase its biomass by 8 times every 3 days. A start-up system might include 4 raceways each of the following surface areas: 32 m^2, 250 m^2, and 2000 m^2. Each 32 m^2 raceway can be stocked with one 400-liter vat culture plus enough additional water to fill the raceway. When the cultures achieve a density of approximately 10^7 cells/ml (3 days under adequate growing conditions) they are transferred to the next larger set of raceways; the 2000 m^2 raceways are used to stock 4 full-size production modules. The next step is to stock 32 production modules from the initial 4 modules. After a final 3-day growth period, all the remaining modules can be stocked and production can begin. The minimum time from vat culture to full facility start-up is 15 days. Presumably, however, the last stocking step will be staggered so that the modules will not all be ready for harvest on the same day. Also, cloudy weather or other imperfect growing conditions could lengthen the start-up period.

reliability / down time

Barring catastrophe, the start-up raceway system should not be needed most of the time. It will probably be used for production-oriented experiments, or to test improved algal strains.

4.2 General Operations

4.2.1 Water Exchange

Water flow to a single raceway and flow of harvested water from a raceway occur simultaneously. Valves which can be either manually or automatically controlled open to allow harvested water to be pumped from the raceway into the harvester transport channel. Simultaneously, water is valved into the other side of the raceway from the feedwater pipe in the pipe corridor. Both water flows are approximately 20 m^3/min, which is roughly equivalent to the flow rate of water in the raceways themselves. 87% of the water in a given raceway is removed during harvesting.

→ raises question of superior strains dominating after harvest

The remaining 13% is left as seed stock for the next 3-day production cycle. Whether the control of valves to direct water flow to and from the raceway is automatic or not, workers at the facility will monitor this operation. The harvest/recharge operation takes about 100 min per average-sized raceway and about 6 raceways are being harvested at any one time.

4.2.2 Nutrient Supply

don't address real-time monitoring or control wh. is implied by discussion

The growth rate of the phytoplankton is constantly changing during their 3-day growth cycle in the raceways. The input of CO_2 and nutrients into each raceway must parallel this changing growth rate; if not, production will be limited or nutrients will be wasted. Nutrients enter the raceway at the propeller pump discharge diffuser. Each raceway's nutrient pipeline is supplied with a multiple position valve which is controlled by a nutrient flowmeter. Nutrients will be added in proportion to the current growth rate of the phytoplankton as measured by CO_2 uptake, which is more easily monitored than ammonia concentration. (An important task for the proposed experiment is to determine that this fertilization strategy works well in practice.) Nutrients will not be supplied at night unless further study indicates that there is some benefit to doing so.

variable growth rate

Consideration must be given to the logistics of transporting and connecting the liquid fertilizer tanks into the nutrient supply system. It is assumed that loads of nutrient tanks are shipped to Honolulu by barge at 3-month intervals, and that the two facility flatbed trucks are used to transport the DOT tanks from Honolulu Harbor to the Ewa Beach facility. Approximately 3 to 4 work weeks will be required to move the 900 tanks delivered every 3 months. An array of 20 tanks, 16 ammonia tanks and 4 10-34-0 tanks, will be connected to a mixing vessel so that the nurients can be distributed in proper proportion. Half of these tanks will require replacement each day. A small mixing system will be required to dissolve the trace metal mix and combine it with the fertilizer solution.

Carbon dioxide is sparged into the flowing raceway water at 13 CO_2 sumps around a typical 1600 m running length raceway (one sump every 124 m). All 13 of these sumps will operate simultaneously only at the times of highest production rate in a raceway. At other times some fewer number of spargers will operate. A single pH probe at one end of the raceway will monitor the CO_2 content of the water. As the production rate of the phytoplankton increases, an increasing number of sumps are turned on automatically to supply enough CO_2 to sustain rapid growth. On the third day of the production cycle, during the period of highest productivity, all 13 sumps may be required, based on the design assumptions previously stated. Further experimentation into the exact spacing, depth and design of the CO_2 sumps is suggested for the experimental facility proposed in this report.

4.2.3 Evaporation Makeup Water

Because of evaporation losses from the raceway, makeup water will have to be supplied on a daily basis to each raceway, especially during hot, sunny periods of the summer months. The main water supply system will be able to supply water for these evaporation losses. At some time during each day, each raceway will receive a calculated flow of water. The remotely controlled water supply system valves will be turned on for a set period of time until the required quantity of makeup water has entered the raceway. Daily evaporation losses will be monitored at the facility laboratory.

4.2.4 Raceway Cleaning

Only one to propose cleaning

Under the current design, each raceway in the facility will be cleaned on a daily basis. The primary purpose of this cleaning operation is to re-suspend the phytoplankton cells which have attached themselves to the bottom and side surfaces of the raceway. In the University of Hawaii experimental system a curved brush is dusted over the entire area of the raceway each day. A mechanized cleaning machine should provide a similar cleaning action for the production facility raceway and for the foil sections implanted in the raceway. A conceptual drawing of one possible raceway cleaning machine is provided in Figure 3-6. The cleaning machines carry a rotating brush resembling a car-wash brush which spans the raceway and scrubs it clean as the machine moves along at about 2 mph (0.9 m/sec). The strands of the brush are long enough for the axis of the brush to clear the foils. Each raceway is cleaned as near as possible to its harvest time, so that any material brushed off the bottom is likely to be swept away with the harvest. CO_2 sumps and the pumping sump in each raceway will require manual cleaning which will be provided by facility laborers. Part of the staff will be involved in this cleaning operation while the rest will monitor the refilling and draining operations of the raceways currently being harvested. The proposed experiments include trials to determine whether or not a less frequent cleaning schedule can reduce this labor requirement without reducing algal production.

Cleaning is done only during the day. About 11 cleaning machines are necessary to clean all the raceways in a 12-hour period each day.

4.2.5 Raceway Sterilization and Restart

Occasionally the algal culture in a raceway will fail through contamination by competing algae or grazing organisms, or the raceway will become too fouled for an unassisted cleaning machine to handle. In these cases, a more thorough cleaning will be required. At harvest, a raceway will be drained completely. All surfaces of the raceway will be sprayed with a 0.5-1% solution of sodium hypochlorite (similar to the solution now used to clean AAI's macroalgae production tanks in Hawaii) to kill any contaminating organisms. The raceway will then be scrubbed with a cleaning machine; spots the machine misses (such as sumps or areas between foils) will be cleaned by hand. The maintenance crew can make minor repairs (filling small cracks, replacing foils) after the raceway is clean.

The chlorine-laden wash water could present a disposal problem. If it were discharged directly into the harvest system (the only drain system available in the conceptual design) it might kill harvested algae from other raceways, with unknown effects on harvest settling and cell composition. A separate drain system for wash water would add to facility costs, and the chlorinated effluent would be subject to discharge regulations. Therefore, to remove the wash water from a raceway, the raceway will be refilled with clean water and operated without algae for one day. By that time, the chlorine should have dissipated sufficiently to present no disposal problem, and the raceway will be drained into the harvest trench and refilled. Finally, the raceway will be restocked with algae from another module.

4.2.6 Harvesting

Each raceway is harvested every three days; water is removed from the raceway simply by moving the mixing pump outflow to the harvest channel that runs by each raceway. Simultaneously, water is let into the other side of the raceway to replace what is harvested. Several employees throughout the facility monitor the filling operation; since their presence is required mainly at the beginning and end of the operation, they will also be available to help clean nearby raceways.

Each of the four settling ponds included in the conceptual design can hold one-third of the total facility water volume. Every 24 hours, roughly one-third of the total facility is harvested and the water from these raceways is pumped into one of the settling ponds. After filling, the pond is left to stand for 24 hours during which time the *Platymonas* cells will settle to the bottom. (Further experimentation in large-scale settling tanks is recommended in the experimental facility to demonstrate that settling ponds are as effective for harvesting *Platymonas* as small settling tanks are.) After the 24-hour settling period, the valves on the pipelines buried in the floor of the settling pond are opened. Each pond is designed to drain in approximately 6 hours. As the water level approaches the bottom of the pond, some of the settled phytoplankton will probably become entrained in the flowing water. However, the majority of the algae will remain trapped by the aluminum angle sections which form channels across the length of the pond floor. When the water has drained the settled algae is collected by sweeper trucks which use vacuum pumps to suction a 5-m wide swath of algal slurry into tanks on the back of each vehicle. It has been calculated that during an eight-hour period 6 or 7 of these vacuum sweeper trucks moving at about 12 m/min could collect the algae slurry in a single settling pond and transport it to an onsite processing facility.

No further conc. on harvest

The entire harvesting process from the start of pond filling to the collection of the algal slurry will require 3 days. The fourth settling pond which is included in the commercial facility design is primarily a backup which will be brought into use when the other ponds undergo routine maintenance or experience schedule overruns.

4.3 Maintenance

Maintenance needs of major components within the facility were included in this conceptual design and the estimate which follows.

4.3.1 Raceways

Although past soil cement containment projects have reported few maintenance requirements (R. Degraffenreid, Soil Stabilization Mixing, Chino, California, and K. Klein, West Tech Services, pers. comm.), it is envisioned that the large expanses of soil cement used in this project will crack and deteriorate. Thus, maintenance will involve sealing these cracks, sealing the raceway surface itself where required, and rebuilding berm walls which may be damaged by routine use of the cleaning machines or other accidental causes. Major cracks will be locally excavated and then resealed with a concrete grouting. For minor cracks and surface damage to the raceways which might affect their permeability, a chemical sealant like Parabond will be used. Parabond is an inexpensive polymer product which is used to stabilize sand or clay. Parabond, together with fine sand and membrane liner backing cloth, has even been used to form water containment reservoirs on the Big Island of Hawaii. The amount of Parabond required for regular raceway maintenance in the raceways will be a function of how impermeable the original soil-cement lining system is. A test of the biocompatibility between Parabond and Platymonas is suggested as one of the experimental facility tests in this report.

4.3.2 Pumps and Valves

The maintenance requirements on a pump or valve in continual saltwater service can be very high. Corrosion is a major problem and a complete overhaul of pumps and valves will be required more frequently for saltwater pumping than for fresh water. In Hawaii's humid environment, electrical contacts can also corrode easily. A semi-annual lubrication and inspection program of all valves and pumps will be required for the facility. In addition, every two to three years valve seals will require replacement and drive mechanisms will require overhaul. Since pumps that are fitted with special stainless steel bowls, propellers and shafts were selected for this facility, major pump overhauls to replace sealed bearings, bowls and shafts can probably be done every five years. A number of surplus pumps, possibly equalling 1/4 of the total number of pumps in service, will be rotated into duty as other pumps are pulled for overhaul.

4.3.3 Pipes

The majority of the pipelines laid throughout the commercial facility are on the surface. However, branch lines from the feeder pipelines are buried under a roadway between the pipe corridor and the pumping sump end of each raceway. The crushing loads due to heavy flatbed trucks and other large vehicles which will regularly circulate along these roads, could cause damage to the buried pipelines, so maintenance of these lines will be required. The surface PVC pipe will be embrittled by the sun, despite painting and other measures used to cut down the effects of sunlight and ozone. This embrittlement will weaken the pipe and make it more susceptible to damage as it ages. Therefore, pipe maintenance requirements will increase in later years. The major maintenance requirement of the pipelines during the early years of the facility operation will be from accidental damage.

4.3.4 Roads

The feeder roads and roadways which separate raceways throughout the facility are undeveloped dirt roads. The roads may need to be oiled if they are a source of dust in the raceways during dry conditions. Due to normal use and the effects of the environment, these roadways will require fill work on an annual basis and regrading every 2 to 5 years, dependent upon the quantity of traffic they handle.

4.3.5 Harvesting System

The harvest settling ponds will be in continual use and will handle a large amount of heavy traffic. The aluminum channels attached to the bottom of the settling pond will be easily bent and displaced by the pumping trucks collecting the algae slurry. Both the settling pond surface and the channel sections will have to be inspected at the end of each 3-day settling pond cycle. Reanchoring or replacement of the aluminum channel sections will take place at this time. Parabond will also be used in the settling ponds to treat minor cracks and parts of the pond where the surface has deteriorated. A major overhaul of the settling ponds will be required every two to three years.

4.3.6 Moving Equipment

The operation of the commercial production facility will depend heavily on its fleet of moving equipment. As has been previously mentioned, a complete garage facility has been included in the conceptual design and regular maintenance of the cranes, forklifts, utility vehicles, trucks, cleaning machines and harvesting vacuum sweepers will be carried out there. It is desirable to extend the service life of the special equipment, such as cleaning machines and harvesting pump trucks, as long as possible, so an especially rigorous maintenance program will be required for them. It is assumed that other commercial vehicles will be replaced approximately every eight years.

4.4 Manpower Requirements

Manpower requirements were estimated as follows:

Harvesting: 8 laborers, 1 supervisor (1 shift). These workers drive the harvesting machines in the settling ponds to collect the algal slurry and drive the machines to the processing facility. The supervisor oversees the filling, draining, and harvest operations.

Raceway cleaning machines: 22 laborers (2 shifts of 11 each), 3 supervisors. These workers control the raceway cleaning machines (one worker per machine per shift) and clean surfaces such as sumps that the machines cannot reach.

Monitoring and assistance with cleaning: 15 laborers (3 shifts of 5 each), 3 supervisors. These workers monitor harvesting and filling of raceways and assist the cleaning machine operators in raceway cleaning operations.

Nutrient mixing and delivery: 3 laborers, 1 supervisor. These workers change the nutrient tanks as required and monitor the nutrient delivery system.

Electrical/mechanical maintenance: 21 laborers (3 shifts of 7 each), 4 supervisors, 2 technicians. These workers are responsible for repairs and maintenance throughout the facility, such as pump repair and replacement, raceway patching, and vehicle maintenance.

Support services (Lab technician, programmer, custodians, guards, office workers): 15 laborers, 2 supervisors, 2 technicians. The lab technician maintains the back-up *Platymonas* cultures and performs chemical and biological analyses. The programmer is responsible for the computer which monitors and controls CO_2 input, nutrient flows, and environmental monitoring and recording. Several office workers, custodians, and guards are required for a facility of this size.

Administration: A facility manager, an assistant manager, and a secretary are required to administer the overall operation.

4.5 Emergency Procedures

Improve reliability

Any one of a number of major system failures could cause a loss of production. Contingency plans have been prepared for a number of these obvious problems and are described below:

4.5.1 Power Failure

Included in the facility design is adequate emergency generating capacity to power all pumps, CO_2 blowers and other electrical equipment in the event of a power blackout. In the event of a power blackout, the pumps used to fill the settling ponds will be returned to service almost immediately. The pumps at each individual raceway are less critical, since adequate berm height at the low end of the raceway has been provided to catch the entire raceway water volume. The raceway propeller pumps will be added to the generator load sequentially after the harvestor pumps have returned to normal operation so that the generators will not have to cope with the extra load of starting all the pumps at once. The rest of the electrical equipment will then be brought on line.

4.5.2 Pump Failure

Failure of an individual pump in a raceway could result in the loss of 4% of the total facility production during that 3-day cycle. To replace a failed pump, hydraulically operated portable pumps which are mounted on a truck and supplied with their own diesel hydraulic power supply (see Appendix 4 for further details) can be moved into position and take over pumping operations in a very short time. The emergency pumps are used to complete the three-day production cycle, at which time the raceway is drained and the failed propeller pump is replaced with an operational unit. These same portable hydraulic pumps can also be used to replace a failed harvestor settling pump.

4.5.3 Loss of CO_2 or Nutrient Supplies

Not much of a safety margin

Storage of liquid CO_2 has been provided for one day's operation in case of a brief interruption of CO_2 supply. The volumes of CO_2 required and the cost of compression for storage do not allow storage of CO_2 in case of a long-term supply interruption.

In the event that some problem prevents shipment of fertilizers to the facility and its 3-month supply is exhausted, locally available (but more expensive) fertilizers can be purchased. Nutrients can be batch-supplied to the raceways from mobile tanks on utility vehicles if the nutrient feed system is shut down.

4.5.4 Harvester Failure

Other than settling pond pump failure, other failures possible in a settling pond include major structural damage to the pond lining or clogging of the buried drain pipe lines. No contingency plans have been prepared for these emergencies if they should occur while the pond is full of water. However, the fourth settling pond should provide backup for the harvesting system.

5.0 ECONOMICS AND SENSITIVITY ANALYSIS: HAWAII FACILITY

After cost estimates for the Hawaii facility were finalized, the computer model was used to derive a baseline estimate of the discounted breakeven price of algae produced by the facility. Then model input parameters that were uncertain, and that had a significant impact on algae price, were varied over their real or presumed range of uncertainty. At first, each parameter was varied independently of all others so that the relative impact of each parameter on algae price could be judged. In this sensitivity analysis, the relative importance of a parameter was strongly affected by the range over which it was varied; a parameter whose value is known closely (such as pump cost) was varied over a small range, while a parameter whose value is known less precisely (such as foil cost) was varied over a relatively large range. The sensitivity analysis was intended to guide the development of the scaled experiment by revealing which parameters had the greatest impact on algae cost. Experiments could then be designed to reduce uncertainty about the most critical parameters, improving predictability of the cost of algae grown in the system.

The model was also used to evaluate the impact of several different potential scenarios on algae cost. These scenarios included the use of a novel method for extracting CO_2 from air, the absence of foils, and the substitution of airlifts for propeller pumps in the raceways. Values more optimistic than the baseline for several parameters were combined in an effort to determine the potential for lowering algae cost below the baseline level. Models of processing systems were added to the main model, and breakeven costs were calculated for the energy products. Finally, the impact on algae costs of a potential byproduct (shellfish grown on unharvested algae) was modeled.

5.1 Baseline Case

5.1.1 Baseline Parameter Values

Tables 5-1 through 5-4 list the values of input parameters used in the baseline cost estimate. Biological parameter values were taken from UH algal raceway data. Engineering parameters were specified by the facility design or were derived from manufacturers' statements, raceway data, and standard references. Construction costs were estimated by MOE using vendors' quotes and standard references (Appendix 4). Financial parameters were chosen to resemble those currently used by SERI as a reference case (Hill et al., 1984), and to conform to current economic conditions (e.g. taxes). Several items that require further explanation are listed below.

ITEM	VALUE
Daily solar constant (kcal/m^2-day)	5000
Photosynthetically active radiation (% of total)	45
Photosynthetic efficiency (% of PAR)	12.2
Carbon dioxide uptake efficiency (%)	70
Algal lipid content (% AFDW)	15
Algal protein content (% AFDW)	50
Algal carbohydrate content (% AFDW)	35
Algal carbon content (% AFDW)	50
Algal nitrogen content (% AFDW)	0.075
Algal phosphorus content (% AFDW)	0.005
Algal ash content (% dry wt)	8
Concentration of nitrogen in medium (mmole/l)	0.5
Concentration of trace metal mix in medium (mg/l)	1.55
Energy content of lipid (kcal/g)	9.3
Energy content of protein (kcal/g)	5.7
Energy content of carbohydrate (kcal/g)	4.2

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Table 5-1. Baseline biological/environmental parameters used in Hawaii commercial culture facility economic model.

ITEM	VALUE
Raceway width (m)	10
Raceway depth (cm)	12
Average raceway running length (m)	1748
Number of raceways	234
Harvest frequency per raceway (#/day)	0.33
Proportion of water exchanged at harvest (%)	87
Raceway roughness coefficient (m^1/6)	0.015
Raceway water velocity (cm/sec)	30
Distance between foil rows (m)	3
Foil angle (degrees)	20
Water supply pumping head (m)	46
Evaporation rate (cm/yr)	180
Water supply pump efficiency (%)	70
Raceway pump efficiency (%)	80
Harvest pump efficiency (%)	80
Number of harvest ponds	4
Total area of harvest ponds (ha)	50
Efficiency of harvesting (%)	80
Distance between carbon dioxide sumps (m)	124
Capacity factor (days/yr)	345
Width of roads (m)	5
Area of feeder roads (ha)	27.8
Area of buildings (ha)	1.1
Area of storage (ha)	0.18
Area of effluent trench (ha)	0.07

high for just settling

Table 5-2. Baseline engineering parameters used in Hawaii commercial culture facility economic model.

ITEM	BASELINE VALUE
Operating costs	
Land lease (\$/ha-yr)	400
Electricity cost (\$/kwh)	0.11
Ammonia cost (\$/MT)	425
Phosphate fertilizer cost (\$/MT)	358
Carbon dioxide cost (\$/MT)	25
Trace metal mix cost (\$/MT)	200
Number of laborers	84
Laborer cost (\$/man-yr)	17000
Number of supervisors	14
Supervisor cost (\$/man-yr)	21000
Number of technicians	4
Technician cost (\$/man-yr)	24000
Administration cost (\$/yr)	95000
Insurance (% of capital costs)	1
Capital costs	
Land preparation (\$/ha)	537
Utility installation (\$)	375000
Road grading cost (\$/m^2)	0.88
Fences (\$)	409345
Raceways:	
Fixed costs (pump sump, pipes; \$/rcwy)	16447
Pumps (\$/unit + installation)	20000
Soil cement liner (\$/m^2)	1.93
Rough construction (\$/m^2)	0.66
Leveling (\$/m^2)	0.31
CO sumps (\$/unit)	1567
CO delivery pipe (\$/rcwy)	5563
Foils (\$/row)	103
Nutrient delivery system (\$)	104294
Water supply system (\$)	1648896
CO delivery system (\$)	1141238
Backup generators (\$/unit)	100000
Settling ponds (\$/unit)	711867
Harvest trenches (\$)	1087670
Effluent trench (\$)	530417
Buildings (\$)	1850000
Storage facilities (\$)	322062
Moving equipment (\$)	1530000
Permits (\$)	50000
Engineering (% capital costs)	5
Contingency (% capital costs + eng.)	15

Table 5-3. Baseline cost parameters used in Hawaii commercial culture facility economic model.

ITEM	BASELINE VALUE
Debt ratio (% of total investment)	50
Common stock ratio (% of total investment)	40
Preferred stock ratio (% of total investment)	10
Nominal return on debt (%)	15
Nominal return on common stock (%)	12
Nominal return on preferred stock (%)	11
Inflation rate (%)	6
Capital cost escalation (%)	0 ?
Operating cost escalation (%)	0
Maintenance cost escalation (%)	0
Facility lifetime (years)	25 (tax lifetime?

Table 5-4. Baseline financial parameters used in Hawaii culture facility economic model.

Solar Radiation and Algal Conversion Efficiency

Average daily solar radiation at the University of Hawaii ranges seasonally from 4300 to 5500 kcal/m^2-day and has averaged 5000 kcal/m^2-day over a 50-year period (P. Ekern, University of Hawaii, unpublished data). The light levels at the Ewa Beach site should be similar (P. Ekern, pers. comm.), so a baseline value of 5000 kcal/m^2-day was chosen. Photosynthetically active radiation (PAR) was assumed to be 45% of total solar radiation. Photosynthetic efficiency of the algae as a percentage of PAR was assumed to be 12.2%, based on Laws' (1984) measurement of 11% in the experimental raceway at an assumed PAR of 50% of total solar radiation.

higher than empirically experienced

Algal Composition

15% lipid 35% Carbo 50% protein

The composition of Platymonas grown in the algal raceway is about 50% carbon, 7.5% nitrogen, and 0.5% phosphorus by ash-free dry weight. The cells are about 50% protein, 35% carbohydrate and 15% lipid, again by ash-free dry weight (ignoring the possible presence of intermediate compounds) and the ash content is 8% of dry weight (E. Laws, pers. comm.). Energy content of protein, carbohydrate, and lipid are 5.7 kcal/g, 4.2 kcal/g, and 9.3 kcal/g, respectively (SERI recommendation).

Water Requirements

Platymonas grows best on a 3-day dilution cycle in the experimental raceway; replacing 87% of the culture medium every three days gives rise to a "growth spurt" on the third day that is a major reason for Platymonas' high production rate (Laws, 1984). These parameters were assumed to be fixed by the requirements of the alga. Average yearly net evaporation in the Ewa Beach area is about 180 cm/yr. (National Weather Service, Hawaii Regional Office).

The baseline system does not recycle any of its effluent water, for three reasons:

1. Seawater is readily available at the site.
2. The ability of Platymonas to maintain high production rates in recycled culture water has not been established.
3. If the effluent water is recycled, unharvested algae will be returned to the raceways. Over time, this procedure may select for unharvestable cells, reducing harvest efficiency.

recycle contamination

Capacity Factor

Capacity factor is defined as the number of effective culture days per year. In Hawaii, the facility can be operated year-round, but individual raceways will be out of production at times because of culture failure or maintenance. It is assumed that each raceway will be drained and sterilized every two months (a two-day process, see Facility Operation, Section 4.2.5) and that each raceway is off line for repairs an additional 8 days per year. The total downtime is 20 days/raceway-year, so the baseline capacity factor is 345.

Harvest Efficiency

80%

The settling ponds are assumed to capture 80% of the algal biomass. This percentage is at the low end of settling percentages measured in the small-scale experiments done with Platymonas, and within the range of removal efficiencies obtained by rapid settling of other algae (Koopman et al., 1980). On the basis of the solids content measurements during the settling drum experiments, a solids concentration of 10% was assumed for the settled algae. These assumptions must be confirmed by experiments on a larger scale.

Nutrient Costs

70% CO_2 efficiency

The baseline price for CO_2 is \$25/MT, based on a quote from R. Fujita of PRI that the price would be less than \$25/short ton. Laws (1984) measured a CO_2 utilization efficiency of 69% in the experimental raceway; the baseline value is assumed to be 70%. Higher efficiencies may be possible, since the experimental raceway was not optimized for efficient use of CO_2.

Non-carbon nutrient costs are based on quotes from Western Farm Service, Inc. of Watsonville, California (B. Witmer and W. Collins). The baseline price of anhydrous ammonia is \$425/MT. This high price is the result of shipping costs from the West Coast, which may be as high as \$95/MT California-Hawaii plus another \$25/MT to ship the empty fertilizer tanks back. Nevertheless, the high nitrogen content of anhydrous ammonia (82%) justifies its use. Anhydrous ammonia is not produced in Hawaii; the least expensive locally available nitrogen fertilizer appears to be UAN-32, a liquid mixture of urea and ammonium nitrate with a 32% nitrogen content from Brewer Chemical Corp. At about \$250/MT, UAN-32 costs about \$780/MT nitrogen, while ammonia at \$425/MT costs \$518/MT N. Considerable savings may be possible if ammonia shipments from Alaska can be transferred to barges bound for Hawaii without additional trucking (B. Witmer, pers. comm.).

The phosphate source is a liquid fertilizer with an analysis of 10-34-0. It is relatively inexpensive and is suitable for mixing with water and ammonia for distribution to the raceways.

$CC = \$66 \times 10^{6}$ yield Baseline 58939

The baseline cost of this fertilizer is $358/MT including shipping. Ammonia requirements are adjusted to allow for the nitrogen contributed by the 10-34-0 fertilizer.

In the Hawaii experimental raceway, a chelated trace metal mix is added to the culture medium. The baseline price for a dry mix of the proper composition is $200/MT, again based on a quote from Western Farm Service.

$\$66 \times 10^{6}$ CC

5.1.2 Baseline Algae Cost

$366/MT ($398/MT AFDW)

The cost of algae grown in the baseline culture facility is estimated to be $366/MT ~~dry~~ weight ($398/MT AFDW) ~~on a net~~ yearly production of 58,939 MT dry weight (54,224 MT AFDW). These cost calculations ~~assume~~ that the algal raceway ~~and harvest~~ experiments can be scaled up successfully to production scale, but that few changes are made to the system. The cost of the raceways dominates the facility capital cost, with the settling ponds next in magnitude (Table 5-5, Figure 5-1). Total facility capital cost is ~~$66 million including 15% co~~ntingency and 5% engineering fee. ~~The largest single cost is the~~ foils; the liner cost is next largest (Figure 5-1). CO_2 purchase is the largest operating cost; non-carbon nutrients, interest and depreciation, labor, utilities, and maintenance are other important costs (Table 5-6, Figure 5-2).

5.2 Sensitivity Analysis: Biological, Engineering, and Cost Parameters

Following the baseline cost calculation, individual parameters were varied to determine their impact on algae cost. Table 5-7 lists the parameters tried, the ranges tested for each parameter, and the algae cost range produced. Some parameters (for example, dilution rate) were not varied because they were assumed to be fixed by the requirements of the chosen species. Other parameters (for example, minor cost items) were not tested because their impacts on total algae costs would have been minimal. Figure 5-3 illustrates the magnitude of the cost variation caused by the most important parameters.

5.2.1 Photosynthetic Efficiency

$489 - 287 (8% - 18%)

Photosynthetic efficiency has the largest impact on algae ~~cost:~~ $489/MT dry weight at the lower limit of 8% efficiency to $287/MT at the upper limit of 18%. The lower limit is based on ~~measurements of 8-10% efficiency in~~ recent wintertime experiments where reduced temperature may have been a factor (SERI Biomass Program Monthly Report, January 1985). It is likely that the yearly average efficiency will substantially exceed 8%. The upper limit was taken for comparison with SERI estimates of maximum achievable efficiency (Hill et al., 1984). Platymonas has exhibited single-day efficiencies as high as 26% on the

CC

ITEM	COST	% OF TOTAL
Engineering & Permits	$2,794,926	4
Land Preparation	393,842	1
Utilities, Roads, Fences	1,925,010	3
Buildings & Storage	2,172,062	3
Raceways	40,874,681	62
Water Delivery	1,648,896	2
CO_2 Delivery	1,141,238	2
Nutrient Delivery	104,294	0
Waste Disposal	530,417	1
Generators	592,934	1
Harvest Ponds	3,935,138	6
Equipment	1,530,000	2
Contingency	8,646,516	13
Total Costs	$66,289,953	100

depreciable vs non-depreciable?

Table 5-5. Baseline capital costs for Hawaii commercial algae culture facility.

OC

ITEM	COST	% OF TOTAL
Labor	$1,818,000	10
Administration	95,000	1
Land Lease	293,202	2
Utilities	1,800,146	10
Interest	2,561,444	14
Depreciation	2,134,560	12
Carbon Dioxide	4,442,020	24
Ammonia	2,665,752	13
Phosphate	871,743	5
Trace metals	15,224	0
Maintenance:		
Raceways	710,672	4
Roads & Fences	154,617	1
Bldgs. & Office Equip.	121,575	1
Pumps	62,304	0
Pipes	89,179	0
Waste Channel	14,886	0
Total Maintenance	1,153,234	6
Insurance	548,985	3
Total	$18,399,309	100

Table 5-6. Annualized operating costs for baseline Hawaii culture facility.

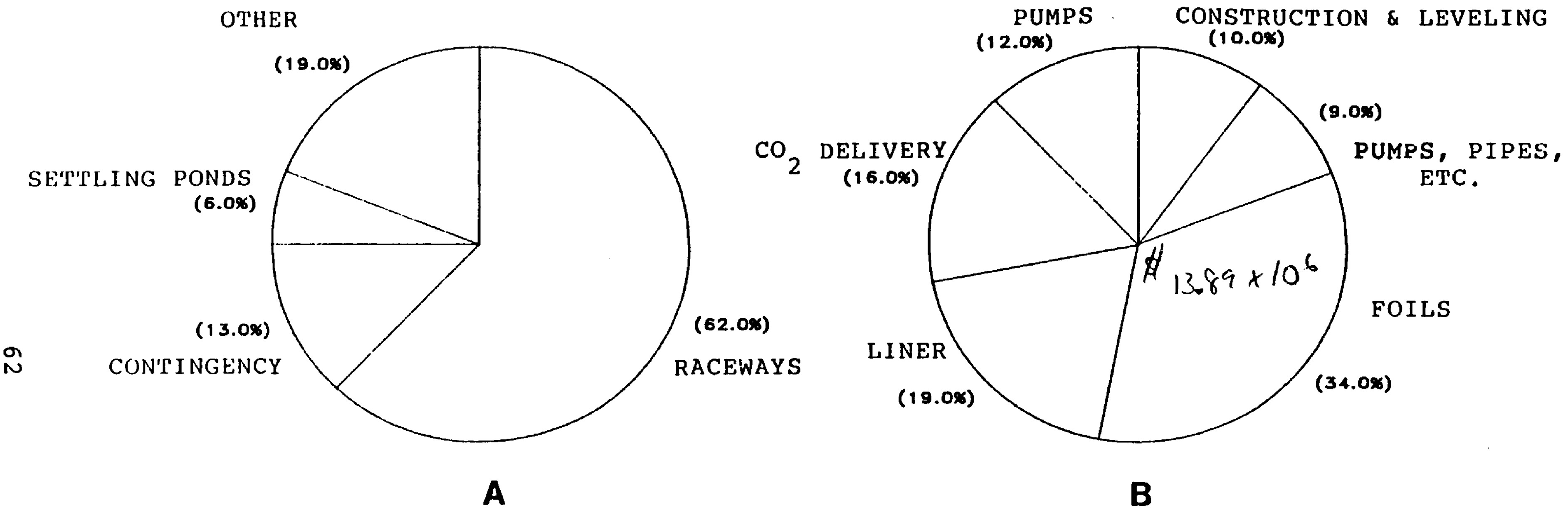

Figure 5-1. Relative cost contributions to Hawaii baseline capital costs (A) and raceway costs (B).

$\Sigma\ 40.87 \times 10^6$

So foils = $.34 \times 40.87 \times 10^6 = \$\ 13.89 \times 10^6$

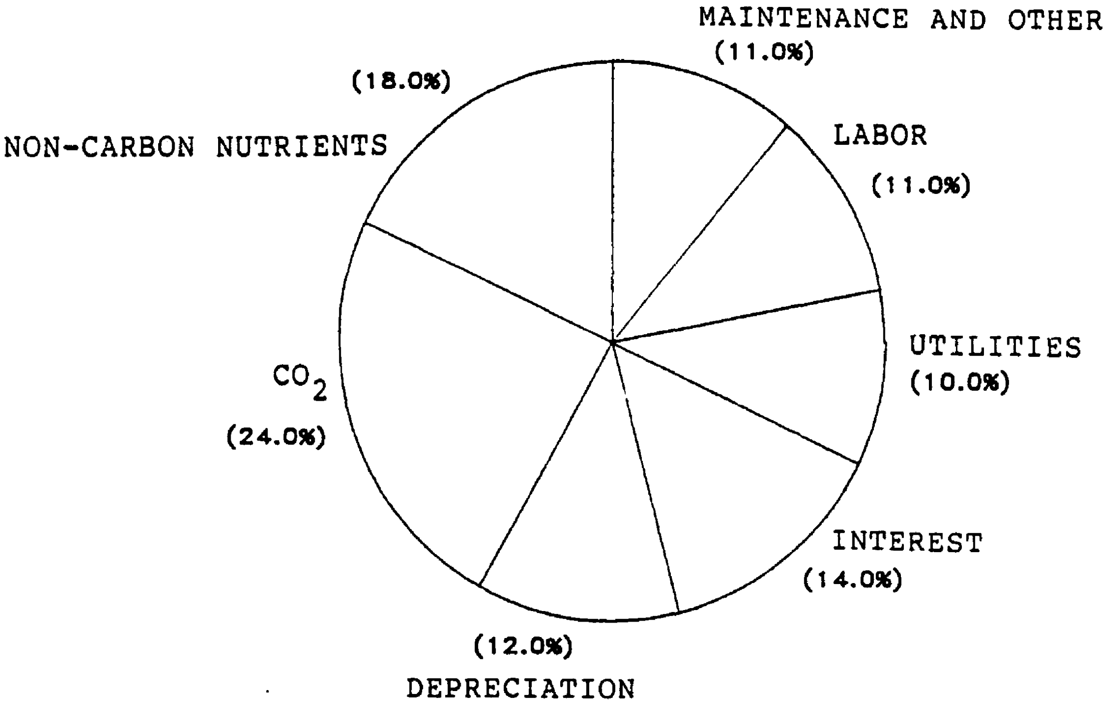

Figure 5-2. Relative contributions to Hawaii baseline operating costs.

PARAMETER	RANGE TESTED Low	High	ALGAE COST ($/MT) Low	High	RANGE
Photosynthetic efficiency (% PAR)	8	18	491	289	202
Harvest efficiency (%)	70	→ 95	417	307	110
Foil cost ($/row)	25	200	338	399	61
Carbon dioxide cost ($/MT)	15	→ 35	335	395	60
Distance between foils (m)	1.5	5	403	350	53
Carbon dioxide uptake efficiency (%)	0.5	→ 0.9	394	350	44
Liner cost ($/running meter)	10	40	353	393	40
Carbon dioxide sump cost ($/unit)	1567	5000	365	402	37
Ammonia cost ($/MT)	250	500	346	373	27
Contingency allowance (%)	10	25	359	379	20
Harvest module cost ($/unit)	711867	→ 2,500,000	365	384	19
Laborers/supervisors (# people)	55/9	110/18	355	374	19
Capacity factor (days/year)	330	360	375	357	18
Raceway cut & fill ($/running m)	3	15	361	377	16
Distance between CO sumps (m)	124	1748	365	350	15
Electricity cost ($/kwh)	0.11	0.16	365	379	14
Water supply pumping head (m)	30	60	359	372	13
Mixing velocity (cm/sec)	15	40	360	373	13
Pump sump & supply pipe cost ($/rcwy	10000	30000	362	374	12
Land rent ($/ha-yr)	200	1000	365	375	10
Raceway pump cost ($/unit)	20000	35000	365	374	9
Nitrogen conc. in effluent (mmole/l)	0	1	362	369	7
Raceway leveling ($/running meter)	1.5	6	361	367	6
Water supply pump efficiency (%)	0.6	0.8	369	363	6
Foil angle (degrees)	10	30	364	370	6
Engineering fee (%)	0.03	0.07	360	366	6
Raceway carbon dioxide delivery pipe	2500	10000	363	369	6
Effluent disposal capital cost ($)	530417	2000000	365	370	5
Road grading cost ($/sq m)	0.5	1	363	367	4
Phosphate fertilizer cost ($/MT)	300	400	363	367	4
Raceway roughness coefficient	0.013	0.02	365	368	3
Raceway pump efficiency (%)	0.65	0.8	367	365	2
Land preparation ($/ha)	250	1000	365	367	2
Evaporation rate (cm/yr)	160	200	365	366	1

Table 5-7. Parametric sensitivity analysis: effect of varying individual parameters over specified ranges.

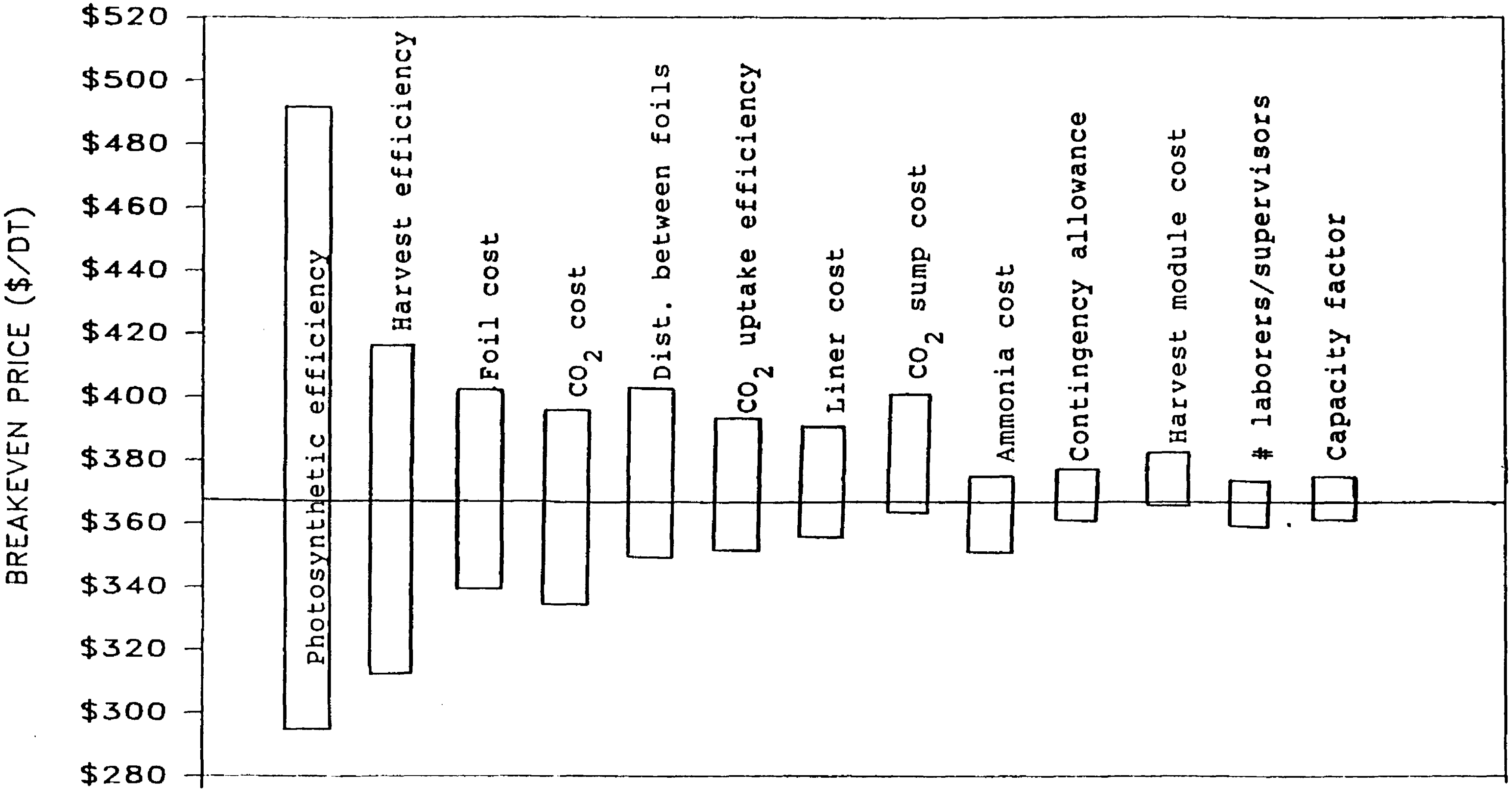

Figure 5-3. Parametric sensitivity analysis: effect of varying individual parameters on discounted breakeven algae cost. Parameter ranges given in Table 5-7. Horizontal line = baseline breakeven price of $366/MT.

highly productive third day of the dilution cycle, but efficiency is much lower on the first and second days. Third-day efficiency averaged 18.8% for a one-month period during March and April 1984 (Laws, 1984). It is unlikely that third-day efficiencies will be improved much if generally accepted theoretical calculations of potential efficiency (e.g. Goldman, 1979) are correct. Further overall improvement is at least conceivable in view of the substantial improvement in production that has been attained with the experimental raceway system in the past two years. The sensitivity analysis indicates that it is worth examining strategies that might improve first- and second-day photosynthetic efficiency in Platymonas beyond present levels.

5.2.2 Harvest Efficiency

The second most important parameter is the efficiency of the settling ponds. The strong effect is not surprising, since any unharvested biomass costs a substantial amount to produce but makes no economic contribution to the facility (at least in the baseline case). Clearly it is worthwhile to test the settling-harvest method on a larger scale and over a longer time period.

or add centrifuges

5.2.3 Foil Parameters

Foil cost has an important effect on algae cost because of the large number of foils required. In the baseline facility, the total cost of foils actually exceeds the cost of the soil cement liner. The distance between foils is also important, primarily because of its effect on capital cost, although there is also an effect on utility costs because foil drag affects pumping head in the raceways. Foil angle, affecting only energy requirements (its effect on productivity is not known), is much less important. The sensitivity analysis suggests that studies on the design and spacing of foils would contribute substantially to facility economics if low-cost, effective foil designs resulted.

5.2.4 Carbon Dioxide

Since CO_2 is required in large quantities as the carbon source for algal production, CO_2 cost and CO_2 utilization efficiency are important to algae cost. CO_2 price is more or less fixed when a site is chosen (although the range tested indicates some uncertainty of what CO_2 cost would be if it were actually purchased from a supplier). It is obviously important to choose a site where CO_2 can be obtained cheaply, unless innovative methods can be used to obtain CO_2 from the air (see Section 5.4.1).

CO_2 utilization efficiency depends on CO_2 sump efficiency, uptake efficiency of the algae, and the amount of outgassing of CO_2 to the atmosphere. It is not clear that the latter two

— is uptake eff. limited by design?

factors can be altered, but they can at least be measured under different circumstances. An efficient CO_2 sump is important, but because of the number of sumps in the baseline case, sump cost is also important. Studies should be conducted to determine the relationships among sump design, distance between sumps, sump efficiency, and sump cost.

5.2.5 Construction Costs

Major construction costs include soil cement liner cost, CO_2 sump cost, and settling pond cost. Other construction costs have somewhat less impact. Construction of the proposed scaled experiment should help refine cost estimates for these components by testing (on a smaller scale) some of the construction methods employed by the conceptual facility, for example laser leveling and soil cement stabilization of raceway structures. Experimental facility construction may also help to reveal any unanticipated construction difficulties that might affect construction costs.

5.2.6 Utility Cost Factors

Utility costs are affected by raceway water velocity, foil angle, raceway roughness coefficient, water supply pumping head, efficiencies of the various pumps, and electricity costs. None of these factors is critical by itself, but a combination of favorable or unfavorable factors could have a significant impact on algae cost.

5.2.7 Other Cost Factors

Other important cost factors are ammonia cost, contingency allowance percentage, labor requirements, and capacity factor. The other listed parameters are less important, affecting algae cost by 3% or less.

5.3 Sensitivity Analysis: Financial Parameters

5.3.1 Financial Leveraging

Changes in the degree of financial leveraging can influence estimated DBEP if costs of equity and borrowed capital differ. In the baseline model, cost of equity capital is more expensive than borrowed capital because contributors of equity capital are paid a required rate of return in after-tax dollars. This is true even though the nominal rate of return on borrowed funds in higher than the nominal rate of return on equity capital (both preferred and common stock). As a consequence, increased leveraging decreases DBEP, all other things held equal. Sensitivity analysis was conducted using debt ratios of 0.75 (high leverage) to 0.20 (low leverage). The ratio of common to preferred stock was kept constant at 4 to 1. Variance in DBEP ranged from $368 for higher leveraging to $392 for the low leveraging alternative.

Inconsequential And Irrelevant

5.3.2 Rates of Return on Equity Capital

Nominal rates of return on equity capital were varied between a low of 5% return on common stock and 4% on preferred, to a high of 14% return on common stock and 12% on preferred. Resulting estimates of DBEP ranges from a low of $369 to a high of $389.

not A factor

5.3.3 Rates of Return on Borrowed Capital

Nominal interest charges were varied between 11% and 18%. Resulting estimates of DBEP ranged from $362 to $391.

5.3.4 Overview of "Best" and "Worst" Cases

To more fully evaluate the sensitivity of financial performance of the farm to alternative financial assumptions, two scenarios were developed. The first, labeled the "Worst" case in Table 5-8 assumes high required rates of return on equity and debt capital and low leveraging. The "Best" case assumes considerably lower rates of return and more leveraging. The results show that differences in breakeven algae prices are significant compared to the sensitivities associated with biological and engineering parameters.

Can you produce ethanol
At this feedstock cost?

Parameter	"BEST" Case	"WORST" Case
Debt Ratio	75%	20%
Common Stock Ratio	5%	20%
Preferred Stock Ratio	20%	60%
Nominal Return on Debt	11%	18%
Nominal Return on Preferred Stock	10%	12%
Nominal Return on Common Stock	11%	14%
Inflation Rate	6%	6%
BREAKEVEN PRICE	$349.34	$418.99

Table 5-8. Estimates of discounted breakeven algae price under two finance scenarios.

5.4 Sensitivity Analysis: Special Cases

5.4.1 Atmospheric CO_2 Collector

Makai Ocean Engineering is involved in the development of an innovative mechanism for the extraction of CO_2 from atmospheric air. The concept grew out of attempts to develop a CO_2 removal device for submersible vehicles. While the CO_2 content of atmospheric air is low, the amount of CO_2 that would actually pass over a given area per day under normal wind conditions is large. A device that could extract the CO_2 efficiently could supply enough CO_2 to support high production levels in an algal raceway.

The CO_2 collectors could take the place of the CO_2 distribution sumps in the baseline facility design. Instead of 13 sumps per raceway, there would be 13 collectors, given the same assumptions about CO_2 dispersion into the water. MOE tentatively estimates that each collector would cost \$2000-4000. The extra capital cost of the collectors would be offset by the elimination of sumps, spargers, and CO_2 supply pipes and blowers. Operating costs (electricity to run the CO_2 collectors) are estimated at \$5/MT CO_2 under ideal conditions. The real cost of CO_2 would presumably be higher than this, but could certainly be well below the cost of purchased CO_2.

All predicated on speculative innovations

To test the impact of CO_2 collection on the production facility, the following modifications were made to the model:

1. Carbon delivery capital costs were set equal to 0.

2. Carbon dioxide blower operating costs were set equal to 0.

3. The cost of CO_2 collectors was substituted for the cost of CO_2 sumps.

4. Two cases were run: an "ideal" case in which collector cost = \$2000 and CO_2 cost = \$5/MT, and a much less optimistic case in which collector cost = \$4000 and CO_2 production cost = \$15/MT.

\$ 298 – 349/MT

In the "ideal" case, algae cost was \$298/MT. The less optimistic case gave a cost of \$349/MT. The system appears to have significant potential for reducing the cost of algae produced in the conceptual facility.

A further advantage of the CO_2 extraction system is the freedom it gives when siting the facility. CO_2 supply is a major constraint on facility siting if the facility must be located near a power plant, CO_2 pipeline, or geological CO_2 source. If this constraint is removed, the facility can take advantage of sites with water resources, better climate, or larger available land areas.

5.4.2 Foils vs. No Foils

Since the foils constitute the single largest capital cost in the baseline model, it is reasonable to reexamine the case for using them. If the increase in photosynthetic efficiency does not outweigh the effects of foil cost and foil drag on the cost of algae produced in the raceways, then the foils are not worth installing. To simulate a no-foil system, the model was modified by setting foil drag and foil cost equal to 0. The algae cost in this modified system was calculated for various photosynthetic efficiencies and compared with algae costs for foil spacings of 3 m between rows (baseline case) and 1.5 m between rows (similar to the present experimental raceway). It was found that photosynthetic efficiency in the no-foil case would have to be 10.2% to give a cost as low as the baseline price, and 9.0% to equal the cost at 1.5 m spacing. These numbers imply that foils would have to increase photosynthetic efficiency by about 18% in the baseline case or 33% in the closely spaced situation. Since foils in the experimental raceway increase photosynthetic efficiency by 45% (SERI Biomass Program Monthly Report, January 1985) or more (Laws et al., 1983), foils appear to be cost-effective.

????

5.4.3 Increased Lateral Foil Spacing

The flume experiments (Appendix 2) suggest that adequate turbulence may be created by foils spaced farther apart laterally than in the baseline system. To simulate this situation, the foil cost and foil drag were reduced by half and the algae cost was recalculated. The new price was $347/MT, a $19 reduction from baseline.

5.4.4 Airlifts vs. Propeller Pumps

Propeller pumps were chosen for the baseline analysis because they are more efficient than airlift pumps for this application. However, propeller pumps have not been tested in the experimental raceway. Propeller pumps may prove unsuitable for *Platymonas* culture, or may reduce photosynthetic efficiency below what is achievable with airlifts. Airlifts are potentially cheaper to construct and maintain than propeller pumps because of the simplicity of airlifts; one blower can run several airlifts, while each propeller pump must have its own motor. On the other hand, airlifts will need deeper sumps than propeller pumps to operate efficiently. To test the potential effect of substituting airlifts for propeller pumps, the following cases were tested with raceway pump efficiency set equal to 30%:

1. Pump cost = $10,000 (airlifts cheaper than propeller pumps)

2. Pump cost = $20,000 (airlifts as expensive as propeller pumps)

3. Pump cost = $30,000 (airlifts more expensive than propeller pumps)

The three cases gave algae prices of $369/MT, $375/MT, and $381/MT, repectively. Apparently the use of airlifts does not drastically increase algae costs unless airlifts are more expensive than propeller pumps. It is well worth testing airlifts vs. propeller pumps, but if airlifts are necessary, the feasibility of the system will probably not be changed substantially.

5.4.5 Optimistic Case

229/MT 12% PSE
175/MT 18% PSE

An "optimistic" but reasonable case was modeled to give some idea of a minimum potential cost for algae produced by the culture facility. The assumptions in this case were:

1. CO_2 produced by MOE CO_2 collectors; collector cost = $2000 each and CO_2 production cost = $7/MT.

2. Harvest efficiency = 90%. from settling ~~from~~ ponds?

3. CO_2 uptake efficiency = 80%.

4. Foil cost = 1/2 baseline, foil lateral spacing = 1/2 baseline.

5. Capacity factor = 355 days/year.

6. Ammonia cost = $375/MT.

7. Labor requirements reduced: 70 laborers, 10 supervisors.

All other parameters were held at their baseline values. All of the parameters that were varied in this case are subject to testing, or at least refinement, in the proposed experimental facility, or are cost estimates that can be refined with further investigation. It may not be possible to investigate the effect of CO_2 collectors in the scaled experiment, since the concept is still being developed, but their potential impact on system costs should be better known.

The algae cost predicted under the above assumptions is $229/MT. Yearly operating costs for this case were $13 million (Figure 5-4). A further, highly optimistic case was tested using the above assumptions, but with photosynthetic efficiency equal to 18%; the algae price for this case was $175/MT. This latter case assumes that additional breakthroughs in algae production are made; the former case requires no real breakthroughs, but does assume that small-scale experiments (such as the harvest experiments and bench-scale CO_2 collector experiments) can be

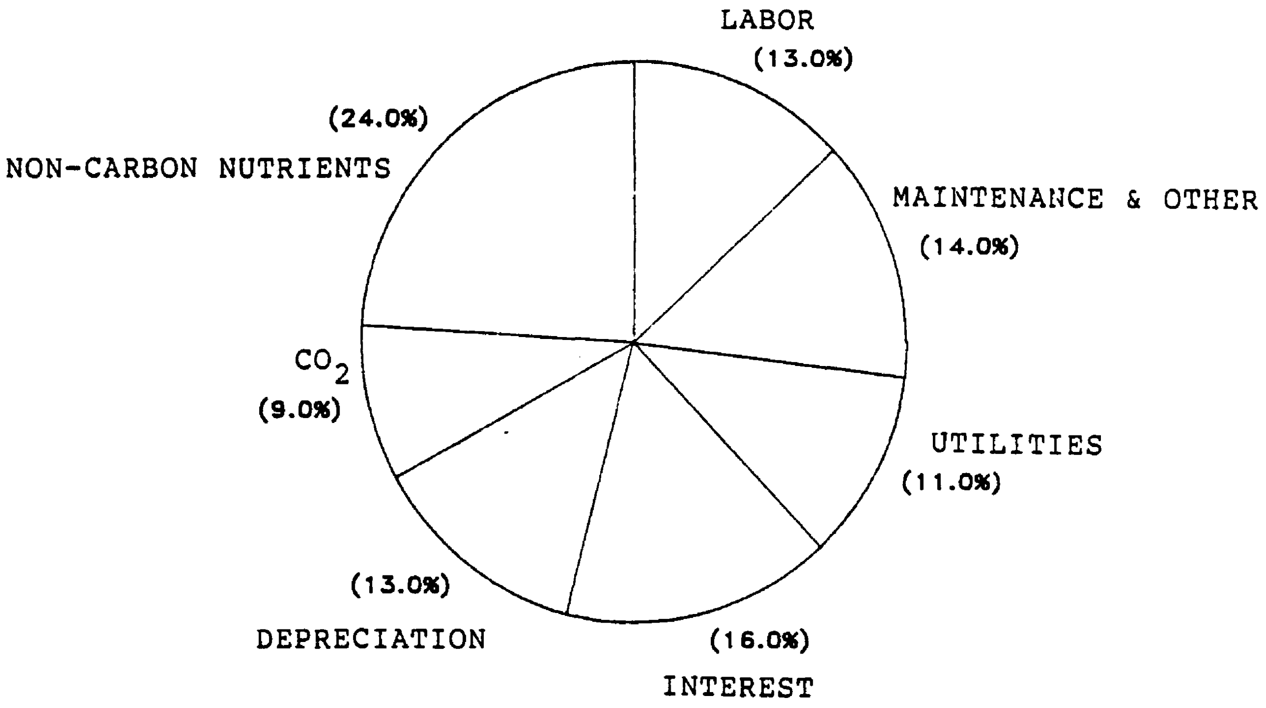

Figure 5-4. Relative contributions to Hawaii "optimistic case" operating costs.

scaled up very successfully. Barring major savings on facility construction costs, these estimates are probably close to the maximum potential of the raceway system without including nutrient recycle from a processing facility.

5.5 Processing Options

The preceding analysis does not deal with the cost of fuel produced from algae grown in the conceptual facility. It also does not take into account the impact of the processing system on the cost of algae. Two processing systems were examined: anaerobic digestion and supercritical water oxidation. The rationale for considering these particular systems has been discussed in Section 2.5.

5.5.1 Anaerobic Digestion

In the process of anaerobic digestion, biomass is decomposed by microscopic organisms. The resulting product is a gas composed of about 60% methane and 40% CO_2, with small amounts of other gases. In order to sell the methane as pipeline gas, the CO_2 must be removed; it can then be recycled to the raceways.

The following discussion is based on information supplied by J. DeVos of Atara Corporation, Paramus, New Jersey (Appendix 5) and V. Srivastava of the Institute of Gas Technology, Chicago, Illinois. The digester is assumed to be a conventional stirred tank reactor. Characteristics of the digester are assumed to be:

Retention time: 10 days
Volatile solids loading rate: 4.01 kg/m^3-day
Total solids content: 10%
Percentage of volatile solids converted: 60%
Gas production: 0.93 m^3/kg, 60% methane
Digester cost: \$180/m^3 (includes all digester capital costs, assumes that other capital costs = cost of digesters; J. DeVos, pers. comm.)
Recycle of non-carbon nutrients: 50% (Ryther, 1982)

Costs for separating the methane from the CO_2 were based on figures supplied by D. Feinberg of SERI. Capital costs for the gas separation plant, but not the digesters, were scaled using a 0.6 power factor. Srivastava et al. (1981) use the same unit per-volume cost for digesters over two orders of magnitude difference in size.

At the assumed loading rate, the required digester volume is about 43,000 m . This volume would be satisfied by six of the 100-ft diameter digester tanks recommended by Atara. The total cost of the digesters (including gas separation system, heaters, mixers, gas compressors, etc.) plus installation, adds slightly more than \$10 million to total facility costs. Total operating costs are similar to those in the baseline case with no

Best cost, good only for Hawaii

\$ 36.43/10^6 BTU Ref.
16.50/10^6 BTU "Best"

processing, but the cost breakdown is different because recycling reduces nutrient requirements while maintenance and utility costs increase (Figure 5-5).

The baseline system produces 614,462 thousand standard cubic feet (MSCF) of methane, about 1/5 of present SNG consumption on Oahu (State of Hawaii Data Book, 1983). It recycles 22,000 MT of CO , about 12% of total facility requirements. The discounted breakeven price for methane produced by this system is \$36.43. This price is well above the SERI projected price goal for methane in the year 2000 of \$7.40/10^6 BTU (Hill et al., 1984; 1 MSCF equals approximately 10^6 BTU). The "optimistic" assumptions listed in Section reduce the required gas price to \$22.57 on sales of 711,307 MSCF. Finally, in the highly optimistic case where photosynthetic efficiency = 18%, the production is 1,049,469 MSCF and the breakeven price is \$17.13. This price is still much higher than Year 2000 projections. Even in Hawaii, where the average retail price of SNG in 1982 was about \$16.50/MSCF (State of Hawaii Data Book, 1983), it appears that methane sales alone (without byproduct credits) would not support the conceptual facility.

In this analysis, no costs have been assigned to digester sludge disposal because of uncertainty about the method of disposal. Sludge can be used as a soil conditioner (Department of Energy, 1983), but the salt content of sludge from a saline-water facility reduces its value for that purpose. The City of Honolulu uses digesters to treat its sewage; the methane is used to dry and burn the sludge, and the ashes are hauled to a landfill (W. Brewer, State of Hawaii Aquaculture Development Program, pers. comm.). This disposal method is obviously undesirable for a fuel-producing facility. One relatively inexpensive method would be land disposal within the facility; the sludge could be pumped to a disposal site and allowed to dry by seepage and evaporation. This strategy would meet environmental objections such as odor and salt contamination of groundwater. An alternative method of waste disposal now under development is supercritical water combustion (see below). A supercritical water reactor capable of destroying the conceptual facility's digestor sludge would be expensive (probably \$5-10 million), but electricity produced by the reactor would defray some of the cost.

5.5.2 Supercritical Water Combustion

Supercritical water combustion is a process recently developed by Modar Corporation of Natick, Mass. (Modell, 1980; see Appendix 6). The following discussion is based on a meeting with M. Modell of Modar.

Supercritical water combustion involves the introduction of a slurry of organic material and a stream of air or oxygen into a reactor containing supercritical water at high temperature and pressure. The properties of supercritical water are different

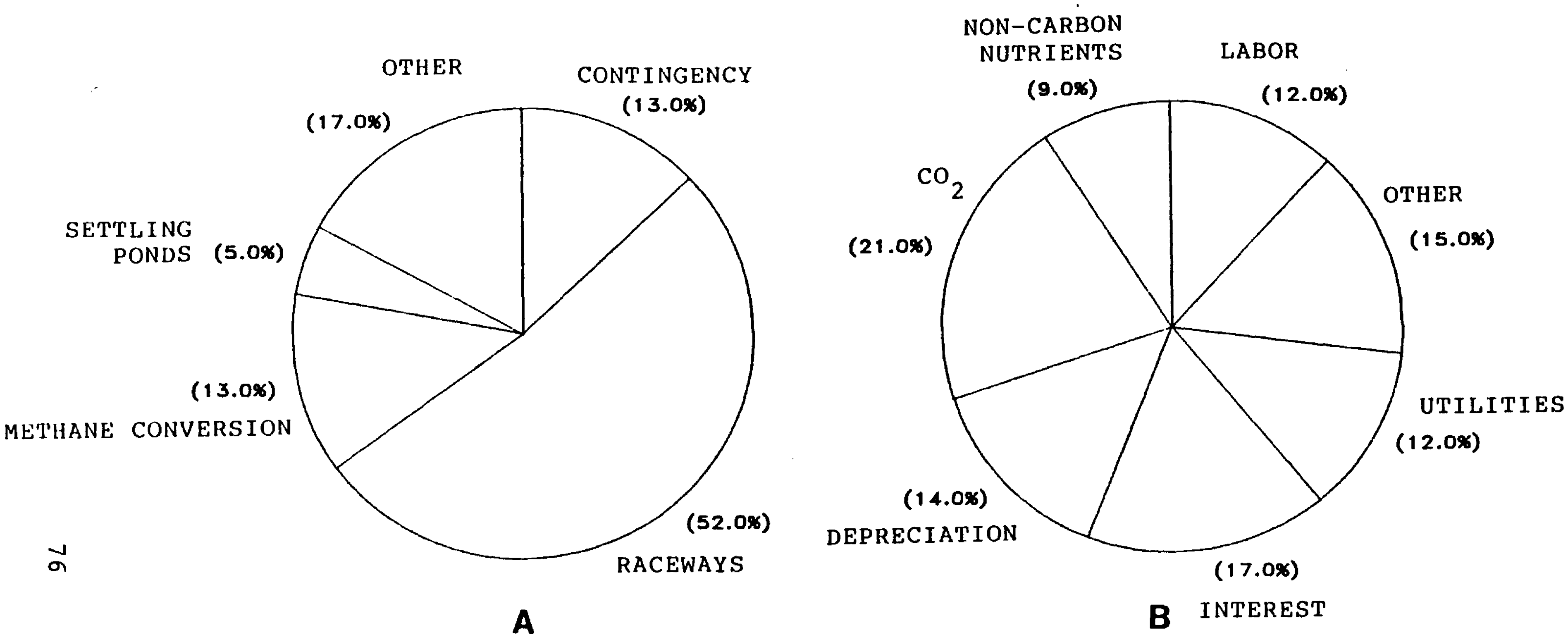

Figure 5-5. Relative contributions to capital costs (A) and operating costs (B) for the Hawaii facility with anaerobic digesters.

from those of ordinary liquid water; both the organic matter and the oxygen are highly soluble in supercritical water. The organic matter oxidizes rapidly and completely if enough oxygen is provided, releasing essentially all of its energy content to the surrounding water. In a well-insulated reactor, very little of the heat produced is wasted, as opposed to the inherent inefficiency of a boiler system.

If the heat of combustion raises the water temperature sufficiently (to at least 450°C), the water loses its ability to dissolve polar salts. The salts precipitate out and can be removed with conventional cyclone separators, leaving a stream of highly pure fresh water. If the supercritical water is hot enough (depending on the heating value of the organic material), it can be used to drive a turbine to generate electricity. Modar has designed an improved turbine which may allow the recovery of as much as 45% of the total energy of the organic material as electricity. The rest of the energy is used to heat and pressurize the incoming water stream and to run the oxygen or air compressor; some energy is lost as waste heat to the effluent water and in lost steam.

Supercritical water oxidation is still in an early stage of development. The demonstration systems produced by Modar have been primarily for the destruction of hazardous organic wastes, taking advantage of the completeness of the oxidation reaction. Nevertheless, eventual development of supercritical water technology for energy production offers interesting possibilities for a biomass-to-energy system.

Potential advantages of a supercritical water reactor for conversion of algal biomass include:

1. The reactor could use a wet algal slurry directly, without requiring additional processing.

2. The process could be highly efficient at converting algal energy content into usable energy.

3. The process is versatile in its fuel requirements; other biomass, conventional fuels, and many other types of organic material could be used to supplement the algal "fuel".

4. Fresh water is a byproduct of the combustion process. Fresh water is a scarce resource in the regions most suited for large-scale algae culture.

5. Much of the carbon in the algal feedstock could be recovered as CO_2 and recycled.

6. No sludge or other algal residue is produced.

7. The process is inherently simple; operating costs are potentially low. Space requirements are minimal.

Potential disadvantages include:

1. Transportable fuel products are not produced. Conceivably the algal slurry might be transported a moderate distance to a local reactor facility.

2. The heating value of a 10% algal slurry (2-3 MJ/kg) is not sufficient to heat the reactor to the temperatures (600-650 °C) at which electrical generation is most efficient. Either the algae would have to be dewatered further or a supplemental fuel (such as dry biomass, coal, or fuel oil) would have to be added.

3. The market value of the recovered salts is probably low (B. Witmer, pers. comm.) and they would therefore present a disposal problem. The salts could be redissolved in the much larger volume of effluent produced by the algae farm without substantially increasing its salinity.

4. The fresh water produced by experimental supercritical water reactors contain significant levels of heavy metals, probably originating from the lining of the reactor vessel. Use of improved reactor materials might solve this problem, or the metals could be removed by ion exchange.

5. Supercritical water reactor components have not been tested for a period of years under operational conditions. Conditions inside such a reactor are highly corrosive.

If the oxygen supply is not sufficient for complete combustion, the organic matter can be converted into smaller molecules such as alcohols and aldehydes which could serve as fuel feedstocks. However, this procedure is not recommended because the products are hydrophilic; too much energy is required to remove them from the water to make the operation worthwhile.

Algal Production Model with Supercritical Water Reactor

Because of the potential for improved energy conversion with a supercritical water processing system, a simple computer model of such a system was added to the algal production model. The system was assumed to use #6 residual fuel oil (the fuel presently used by Hawaiian Electric Company in its power plants) to bring the heating value of the 10% algal slurry up to 4.9 MJ/kg water, which is required for most efficient net energy conversion of 40-45% (M. Modell, pers. comm.). A net energy production of 40% of algal energy content was assumed. In this type of system, the algae can be regarded as a fuel supplement, reducing the need for fossil fuel to produce a given amount of power. At 44.1 MJ/kg, 0.05 kg oil per kg water is required; approximately 45% of the total energy production is supplied by the oil and 55% by the algal biomass.

Capital costs for the supercritical reactor and its associated compressors and other equipment were given by M. Modell of Modar as $10-20 million at baseline production levels. A capital cost of $15 million is assumed in this analysis. A power factor of 0.6 was used to extrapolate reactor capital cost under different production scenarios, as is SERI practice (Hill et al., 1984). Major operating costs are maintenance (5% of capital costs per year) and insurance (already included in the overall model). The labor requirement was cited as 3 full-time personnel; on the assumption that the equipment will be operated 24 hours a day by shift workers, this requirement was increased to 6 workers.

Net energy conversion efficiency of the supercritical water unit was assumed to be 40%. Credit was taken for fresh water production at a rate of $1.05/1000 gallons ($0.27/m^3). It was assumed that 80% of the water entering the reactor can be recovered as fresh water. The precipitated salts are discharged with the farm effluent; no cost is assigned to salt disposal. No credit was taken for CO_2 recycle because the cost of separating the CO_2 from the reactor gas stream (which contains mostly nitrogen brought in with the injected air) was not known. If the cost of extraction is close to that of CO_2 separation from methane (see Section 5.5.1), there appears to be little advantage in separating the gases over simply buying the CO_2 at $25/MT. If CO_2 is scarce or expensive, or less expensive ways are developed to extract the CO_2 (see Section 5.4.1), then recycling the CO_2 becomes an attractive option.

Results

The baseline breakeven price of electricity produced by the supercritical water reactor was $0.113/kwh at a production level of about 28 MW. A credit of $105,000/yr was taken for water production. The "optimistic" case gave a price of $0.080/kwh. The present "avoided cost" rates paid by Hawaiian Electric Company for electricity from alternative energy projects are $0.059/kwh peak and $0.051/kwh off-peak; the peak rate may be lower than justified by present economic conditions (R. Neill, Hawaii Natural Energy Institute, pers. comm.). Conceivably algae culture could play a role where adequate supplies of fossil fuels are difficult to obtain and other biomass sources are limited, such as Pacific islands. In other regions, the cost of algae as a fuel for the supercritical water process would have to be considered in relation to the cost of other available fuel materials.

5.6 Byproduct Option: Shellfish Production

The economics of an algae culture facility cannot be judged by fuel sales alone, even if most of the algal production is used for fuel production. Byproducts of the algae facility will affect the overall revenues of the facility, improving its economic outlook and reducing the price that must be asked for the fuel product in order to achieve a specified return on investment. Potential byproducts of an algae culture system include herbivorous marine animals grown on unharvested algae in the facility's effluent. In the baseline conceptual culture system, 20% of the algal biomass (about 140,000 MT wet weight) is lost in the effluent if nothing is done to capture it.

In order to estimate the potential impact of food production on the conceptual facility, a section was added to the baseline model that modeled the addition of an intensive shellfish culture system to the facility's effluent stream. The shellfish was assumed to be the Eastern oyster, *Crassostrea virginica*, but other types of fish and shellfish could also be grown on the unharvested algae (see Appendix 3). *Platymonas* (as *Tetraselmis*) species have been tested successfully as food for juvenile bivalves, including oysters (Walne, 1970).

The size and cost of the oyster culture facility were governed by the amount of unharvested algae available. Scura et al. (1979) found that oysters in intensive raceway culture removed 88-99% of the phytoplankton from the feed water, and the conversion efficiency of algal biomass to shellfish meat was 11.4%. In this study, it was assumed that the oysters filtered out 90% of the algae fed to them, and that oyster meat production was 10% of the wet weight of the algae consumed.

From MOE's experience in designing intensive shellfish culture systems, oysters can produce about 200 kg live weight/yr per m of culture trench volume; for relatively small systems, the trenches cost about \$160/m^3 volume enclosed, and the overall facility (excluding algae culture system) costs about 4 times the cost of the trenches. These relationships were used to calculate the capital cost of the oyster culture system; a power factor of 0.6 was used to account for economies of scale. Although the high labor requirements of intensive oyster culture systems can probably be reduced by attaching the oysters to ropes or plates in the trenches rather than holding them in trays as is frequently done (R. York, Hawaii Institute of Marine Biology, pers. comm.), the facility would probably still be more labor-intensive than the algae culture facility; it was assumed that the oyster farm employed 100 laborers, 17 supervisors (1/6 of the number of laborers), and 3 technicians, and had the same administrative requirements as the algae facility.

In addition to labor, the major expenses of the oyster facility would be seed (juvenile oyster) purchase, water pumping, and maintenance. Maintenance was assumed to be 5% of capital cost per year. Seed costs were assumed to be \$10/1000 oysters, with a 30% mortality rate (Aquacultural Research Corporation, Dennis, Massachusetts). This cost is probably conservative, since a facility this large would probably have its own hatchery. The amount of water the facility would have to pump is not known;

it was assumed that the algae farm effluent (still concentrated at more than 200 mg dry wt algae/liter) would need to be diluted to achieve efficient use of the algae by the oysters. Epifanio and Ewart (1977) found that the maximum algal ration for C. virginica was about 10 mg/l; if this concentration was exceeded, large quantities of pseudofeces were produced. To dilute the effluent of the baseline facility to this level, a dilution of about 27 times would be required. Power requirements were calculated in the same way as for other algae farm systems based on a 5-m pumping head. The capital cost of the facility effluent system was increased by about 10 times, to $5 million, based on the much larger amount of effluent discharged by the oyster system.

Oyster farm revenues were calculated from oyster production assuming a price of $3000/MT meat weight. (The average wholesale price of aquacultured oysters in the U.S. in 1982 was about $3400/MT meat weight; Anonymous, 1984). Revenues from oyster culture were assumed to start in the second year of operation.

The total capital cost of the hypothetical oyster facility was $23.6 million. Operating costs were $12.7 million/yr. Farm revenues were $36.6 million on a production of 12,200 MT meat weight. Rudimentary though it is, this analysis shows that shellfish production could be a major revenue producer for the conceptual facility. Taking credit for oyster production, the resulting breakeven algae price is $61/MT in the baseline case. In other words, the shellfish supply most of the revenues required for the anticipated rate of return on facility investment, and the harvested algae can be sold at a much lower price than would be possible without byproduct credits.

The number of oysters such a farm could produce is quite large. Total U.S. production of oysters is 40,000-80,000 MT/yr meat weight (Fallon et al., 1984; Lee and Yamauchi, 1980). Most likely a farm as large as the one modeled here would raise more than one product so as not to exceed market demand for any one.

12 / facility

40-80 mt size

6.0 CONCEPTUAL DESIGN AND ECONOMIC ANALYSIS: SOUTHWEST FACILITY

As part of this conceptual design study, it was requested that an estimate be made to transfer the Hawaii commercial facility conceptual design to a site in the American Southwest. Such an estimate was prepared by comparing important site characteristics and analyzing their impact on important facility cost parameters.

6.1 Facility Description

The site selected in the American Southwest is located on the southeastern corner of the Salton Sea in the Imperial Valley of southern California. In Figure 6-1, the commercial facility has been plotted with respect to the Salton Sea and the towns of Niland and Calipatria, California. The microalgae production facility has been sited approximately 1-1/2 miles from the lake shore shown in this 1956 USGS map. The Salton Sea has continued to fill since 1956 and many of the CO_2 wells shown are now underwater (J. Kelly, Dept. of Planning, Imperial County, California). The siting of the facility as shown in Figure 6-1 is therefore a conservative prediction of where the facility might reasonably be located.

The Salton Sea site was selected because the necessary resources are available for a large algae production facility. In particular, saline water is abundant and significant unused deposits of geological CO_2 are available. Water would be obtained from salt water wells located within one-half mile of the Salton Sea shoreline. Shallow water wells of 50 to 150 ft deep will have very good communication with the Salton Sea water if located within one-half mile of the sea shore (F. Welsh, H & W Well Drilling Co., pers. comm.). Salton Sea water is salty (30-40 ppt), and well water in the area can be even more salty (up to 50 ppt for shallow wells). It is estimated that 8 to 10 wells, each supplying approximately 5,000 gpm, would be required to supply the entire commercial facility.

The Salton Sea area is very rich in geological CO_2 deposits. Numerous CO_2 wells were drilled prior to 1950, and the CO_2 was used to make dry ice used in railroad cold storage cars. With the advent of refrigerated storage cars, the CO_2 wells were sealed and abandoned. However, reports from the geothermal energy developers, who have recently drilled deep wells to tap the geothermal steam resource in the region, and conversations with Mr. Frank Welsh, indicate that the CO_2 source is still very active and is difficult to avoid when drilling in the Salton Sea area. CO_2 can be found from 50 to 2800 feet deep. CO_2 obtained from these wells is 98% pure mixed with 2% steam (W. Elders, Earth Science Department, University of California, Riverside, pers. comm.). It is assumed that five CO_2 wells could supply the inorganic carbon requirements of the facility.

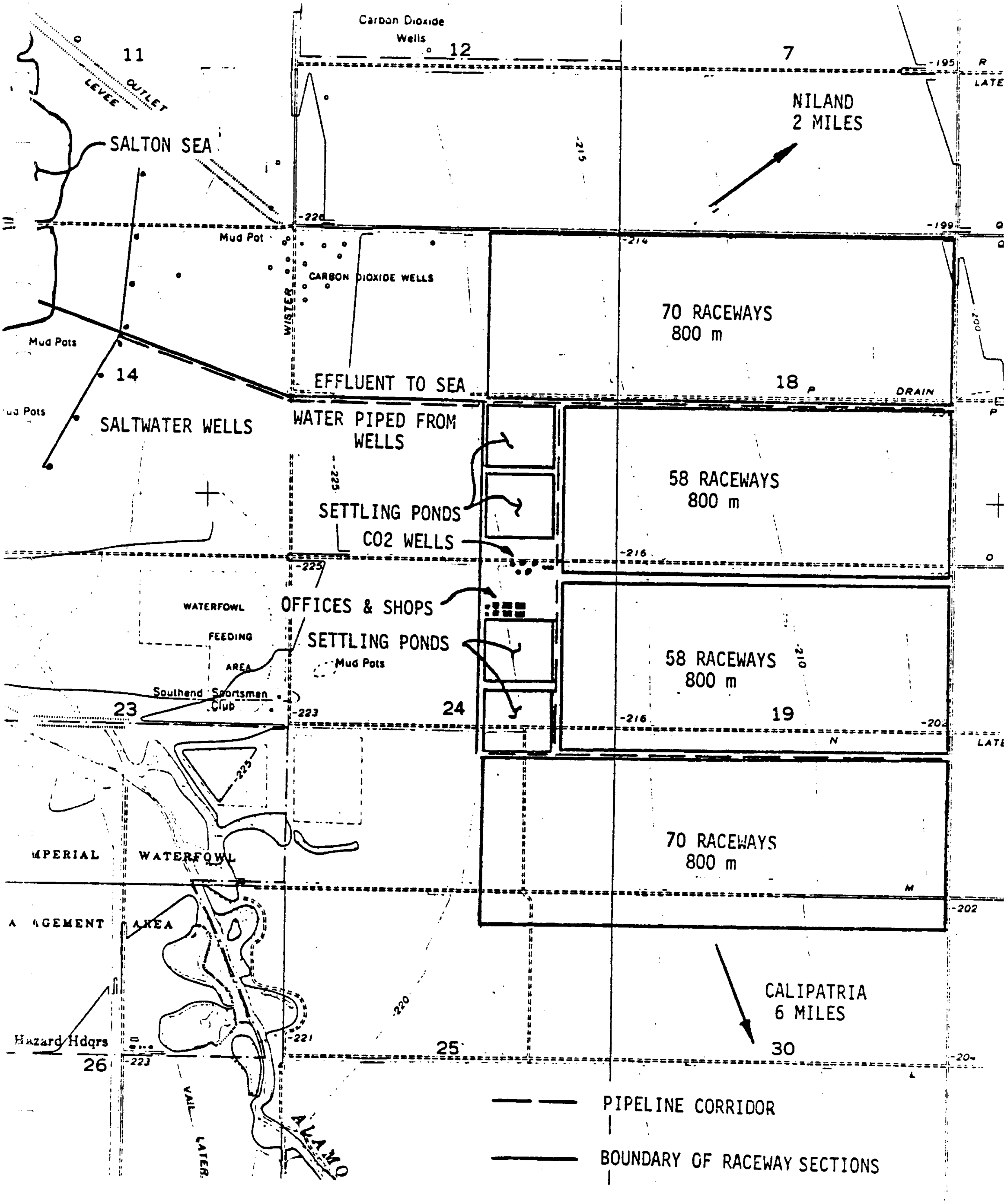

Figure 6-1. Diagram of conceptual Salton Sea culture facility.

Effluent disposal is accomplished by direct discharge into the Salton Sea. Imperial County officials in El Centro, California reported that a past aquaculture facility had received permission to discharge effluent directly into the lake. It is necessary, however, to conduct an environmental impact study and to obtain the required permits before effluent discharge would be allowed. It was assumed, for this conceptual design, that the environmental impact statement would be positive, and the required permits could be obtained to allow such discharge.

The soil structure in the southeastern Salton Sea area is a very fine clay material which could best be stabilized by mixing it with approximately 3% quicklime by weight (R. Degraffenreid, Soil Stabilization Mixing, Chino, California, pers. comm.). The clay itself has a very low permeability, but needs to be stabilized to avoid cracking during periods when the ponds are left dry. The very flat terrain in the Salton Sea area and the very fine clay should facilitate earthwork and keep these construction costs low. The land is currently zoned agricultural, and the proposed aquaculture facility would be considered an agricultural development.

The Salton Sea region contains active geological fault zones. An actual facility in this area would have to be sited carefully to minimize the risk of serious earthquake damage.

6.2 Comparison with the Hawaii Site

The major difference between the facility design for the Salton Sea site and the Hawaii site is the overall shape and layout of the facility. Because of the larger expanses of available land around the Salton Sea area and the American Southwest in general, it was assumed that a more regular, rectangular-shaped facility could be realized. Land would be purchased rather than leased as in Hawaii. The raceways are organized into four major sections with the northern and southernmost sections each containing 70 raceways and the middle sections each containing 58. Harvester settling ponds are located on the western side of the facility, closest to the lakeshore, to allow the shortest run for effluent to the lake. Since most of the CO_2 wells in the area have been permanently capped and abandoned, it is assumed that CO_2 wells would have to be drilled, and that they could be drilled in a location on the western side of the facility. Saltwater wells would be drilled somewhere within one-half mile of the Salton Sea shore; the exact location of these wells would be determined by test drilling prior to the start of construction.

There would be no difference between the raceway construction at the Hawaii site and the California site, with the exception that all the raceways in the California facility would be of equal size (1600 m running length), and 256 production raceways would be built. A separate soil analysis would be required to determine the exact lime requirements in order to stabilize the soil in this area.

The water supply system from the wells to the individual raceways would consist of single 20-inch PVC pipes laid in pipe corridors between the two northernmost blocks of raceways and the two southernmost blocks of raceways. As in the Hawaii facility, this pipe corridor would include water supply lines, nutrient supply lines, CO_2 supply lines and the harvest water return channel. The length of this corridor, the pipelines and channel are shorter in the California facility due to the more regular layout of the facility.

The settling ponds and the harvester supply system have not undergone any major changes in the California facility. The settling ponds are assumed to be the same dimensions as those in the Hawaii facility and their operations would be identical. The open channel which brings harvest water from both sides of the facility to the settling ponds has been designed based on the available land slope in the area, and is 1.1 m wide. To carry effluent from the harvester settling ponds to the Salton Sea, another open channel runs along the western side of the facility in front of the settling ponds and then turns to the sea. The total length of the channel is 4000 m, and the channel is 2.4 m wide. This channel will carry the volume of the settling pond to the sea in the required 6 hours draining time.

The nutrient and CO_2 supply systems would differ very little from the Hawaii facility, except that nutrients would be trucked in from Western Farm Service in Watsonville, CA. A one-month supply of nutrients would probably be stored onsite at all times and shipments of nutrients would be trucked in on an almost daily basis.

It is unknown at what pressure the CO_2 would be obtainable from the wells, so an array of 17 10-psi blowers to deliver the CO_2 from the wellhead to the individual raceways has been included in the California facility design. At one site near the Salton Sea, the CO_2 pressure is 200 psi at 100 ft depth (L. Grogan, Kennecott Corp., pers. comm.). Since the CO_2 distribution system needs only 10 psi, it may be possible to do without blowers.

There has been little change in most of the design details in transferring the Hawaii conceptual design to California. Moving equipment and building requirements were assumed not to change, utility installation was assumed unchanged, total fence length was reduced due to the more regular shape of the facility and the same number of emergency generators were assumed necessary.

The winter climate near the Salton Sea appears mild enough to allow the facility to operate year-round. The average air temperature in January is 13 °C; on average there are 12 frost days per year. Only one snowfall has ever been recorded (Layton and Ermak, 1976). A system with flowing, saline water should be able to endure a small frost period without freezing over. The capacity factor for the California site is assumed to be 345 days/year, the same as for the Hawaii site. The combination of low light levels and low temperature during the winter could cause revenues to fall below operating costs for some period, so the facility might shut down seasonally for economic reasons.

Because of the less stable climatic conditions, the baseline California photosynthetic efficiency is assumed to be 11% of PAR rather than the 12.2% in Hawaii.

All facility maintenance requirements were identical to those used in the Hawaii facility.

6.3 Species Selection

It is difficult to choose species for the conceptual Southwest system for at least three reasons: questions efficacy of concept for southwest U.S.

1. A shallow raceway with foils similar to the Hawaii experimental raceway has never been tested under conditions typical of a Southwest site, so the species that grow best under those conditions are not known.

2. The changing seasonal conditions in the Southwest will probably require that different species be maintained: a summer species, a winter species, and possibly a species for intermediate conditions.

3. The proposed harvest system depends on the observed rapid settling behavior of *Platymonas*. It is not known what other species might be as easy to harvest that would also thrive in the shallow raceway system.

For the purposes of this analysis, it was assumed that algae are found that grow well under conditions typical of the Salton Sea site amd that can be harvested in a similar manner. *Platymonas* itself may succeed during summer in the Southwest, provided that salinity is not too high and that *Platymonas* will tolerate daily water temperature fluctuations. *Platymonas* has been grown in simulated Southwestern water types; simulated Type I water produced better growth than diluted seawater of the same salinity (SERI Biomass Program Monthly Report, January 1985). Also, other species of *Platymonas* may exhibit similar settling behavior (Walne, 1970). It is recommended as an adjunct to the scaled experiment that species screening trials be done in Hawaii-type shallow raceways at a Southwestern site.

6.4 Cost Estimates and Assumptions

Where California facility cost items differ from Hawaii baseline costs, they are listed below:

6.4.1 Capital Costs

Land Costs		
	Assumptions	$3750/ha purchase price
	Cost Reference	$600-2500/acre for low-grade agricultural land; Wiley Corn Real Estate, Brawley, CA
Land Preparation		
	Assumptions	745 ha total facility size
	Cost Reference	10% reduction of Hawaii costs
Survey		
	Assumptions	No change from Hawaii facility (NC)
	Cost Reference	NC
Utilities		
	Assumptions	NC
	Cost Reference	NC
Road Costs		
	Assumptions	37.4 ha of feeder roads.
	Cost Reference	10% reduction of Hawaii costs.
Fence Cost		
	Assumption	Fence around outer perimeter of entire facility, total length 11,208 m
	Cost Reference	10% reduction of Hawaii costs.
Water Pumping Sump		
	Assumptions	NC
	Cost Reference	10% reduction of Hawaii costs.
Raceway Branch Pipeline		
	Assumptions	NC
	Cost Reference	10% reduction of Hawaii costs, does not include valves.
Raceway Construction -- Cut and Fill		
	Assumptions	NC
	Cost Reference	10% reduction of Hawaii costs.
Raceway Liners		
	Assumptions	No change from Hawaii facility, 3% lime-stabilized soil
	Cost Reference	Quick lime obtained at bulk rate, $110/ton, $15/ton shipping from Los Angeles to Salton Sea site. Material costs become $.08/sq ft,

installation costs become $.09/sq ft.

Grading	
Assumptions	NC
Cost Reference	10% reduction of Hawaii costs.
CO_2 sump	
Assumptions	NC
Cost Reference	10% reduction of Hawaii costs, except for diffusers.
Raceway Mixing Foils	
Assumptions	NC
Cost Reference	Installation costs reduced by 10% of Hawaii costs.
Nutrient supply system costs	
Assumptions	6273 m of feed pipe required. One mixing tank and two pumps also required.
Cost Reference	10% reduction in feed pipe and mixing tank costs over Hawaii costs. No change in pump costs.
Water Supply System	
Assumptions	6273 m of the pipe in facility pipe corridor. 6060 m of feed pipe from wells near sea shore to facility. 8 water wells, 17 valves and 9 pumps.
Cost Reference	Pipe cost reduced 10% of Hawaii costs, no change in valve or pump costs, well costs $5000 each (H & W Water Well drillers charge $145/hr, assume one well/day, or $1160/day; $5000 assumed to provide for well testing and lining.)
CO_2 Supply System	
Assumptions	Five CO_2 wells, 6273 m of feed pipe to distribute CO from wells to raceways, 17 blowers and 9 valves.
Cost Reference	Well costs $20,000 per well (H & W Well Drilling estimated 2 days at $5500/day to dig well to 400 ft. Additional $9000 for setup, well lining and testing) Feed pipe costs are assumed to be 10% reduction of Hawaii costs, blower and valves costs are unchanged.
Emergency Generators	
Assumptions	NC
Cost Reference	NC

Harvester Settling Ponds

Assumptions	NC
Cost Reference	The 6-in lime stabilized soil liner was assumed to be 1-1/2 times as expensive as the 4-in raceway liner. Excavation, concrete and pipe costs were assumed to be 10% less than in Hawaii. Pumps and valve costs were not changed.

Harvest System Water Channels

Assumptions	0.15% slope available for the harvest system water channel. 1.1 m wide water channel installed, requiring 11842 cu yd of excavation, 2496 cu yd of concrete.
Cost Reference	Concrete and excavation costs 10% less than in Hawaii.

Effluent Discharge Trench Costs

Assumptions	Slope from facility to Salton Sea is assumed to be 0.16%, 2.4 m wide trench was required to carry 125,000 gpm. 54,597 cu yd excavated, 5035 cu yd of concrete required.
Cost Reference	Excavation and concrete costs 10% lower than in Hawaii.

Building Costs

Assumptions	NC
Cost Reference	NC

CO_2 Storage System

Assumptions	NC
Cost Reference	$0.02/lb shipping costs for steel pressure vessels was eliminated. Net cost difference per lb of CO_2 stored was $.01.

Moving Equipment Costs

Assumptions	NC
Cost Reference	NC

Maintenance Requirements

Assumptions	NC
Cost Reference	NC

6.4.2 Operating Costs

Nutrient Costs

Assumptions	$260/MT ammonia, $270/MT 10-34-0
Cost Reference	Western Farm Supply

Electricity Cost		
	Assumptions	$0.06/kwh
	Cost Reference	Quote of $0.05-0.06/kwh for Salton Sea region.
Labor Costs		
	Assumptions	Laborers: $12,000/man-year Supervisors: $24,000/man-year Technicians: $34,000/man-year
	Cost Reference	Unskilled labor relatively inexpensive in Salton Sea region; supervisors and technicians more expensive than Hawaii

6.5 Algae Costs: Southwest Facility

284 (309) MT   144 "Best"

Given the above assumptions, the discounted baseline price of algae produced by the Salton Sea facility is $284/MT ($309/MT AFDW). The capital cost of the facility is roughly the same as that of the Hawaiian facility; slightly lower construction costs are balanced by the cost of land purchase and a longer effluent trench. Operating costs of the California facility are much lower ($11 million vs. almost $18 million in Hawaii), mainly ~~because of the~~ free CO_2 presumed to be available at the California site but also because of lower costs for non-carbon nutrients, electricity, and labor and the absence of land rent (Figure 6-2). An "optimistic" case was run using the same assumptions as the Hawaiian optimistic case, except that CO_2 collectors were not necessary and ~~nutrient costs~~ were not changed from the baseline case. The optimistic case gave a breakeven price of $217/MT. The "highly optimistic" case of 18% photosynthetic efficiency gave a price of $144/MT. ~~This case~~ is probably less likely for a ~~Mainland site than for~~ a Hawaiian one.

Breakeven costs were also calculated for methane produced by the California facility. Assumptions were the same as for the Hawaii methane option, with the exception that 20% less methane production per unit algae was assumed because of the additional heating requirements for a digester sited in California. Maintaining the digester temperature at 30-35 °C may consume as much as 30% of total energy production if the incoming water temperature is 15 °C (Srivastava, 1984).

\$34.93/10^6 btu → 17.72/10^6 btu Methane

The breakeven price for methane produced by the California facility is $34.93/MSCF on production of 443,834 MSCF. The "optimistic" and 18% conversion efficiency cases gave prices of $26.01/MSCF and $17.72/MSCF, respectively. Although the discounted breakeven price of algae produced in the California facility is calculated to be lower than in Hawaii, methane produced by the California facility has little or no cost advantage over methane produced by the Hawaii facility because of the greater energy required to heat the California digesters. The California facility also benefits less from digester nutrient recycling than the Hawaii facility because of the lower nutrient costs in California.

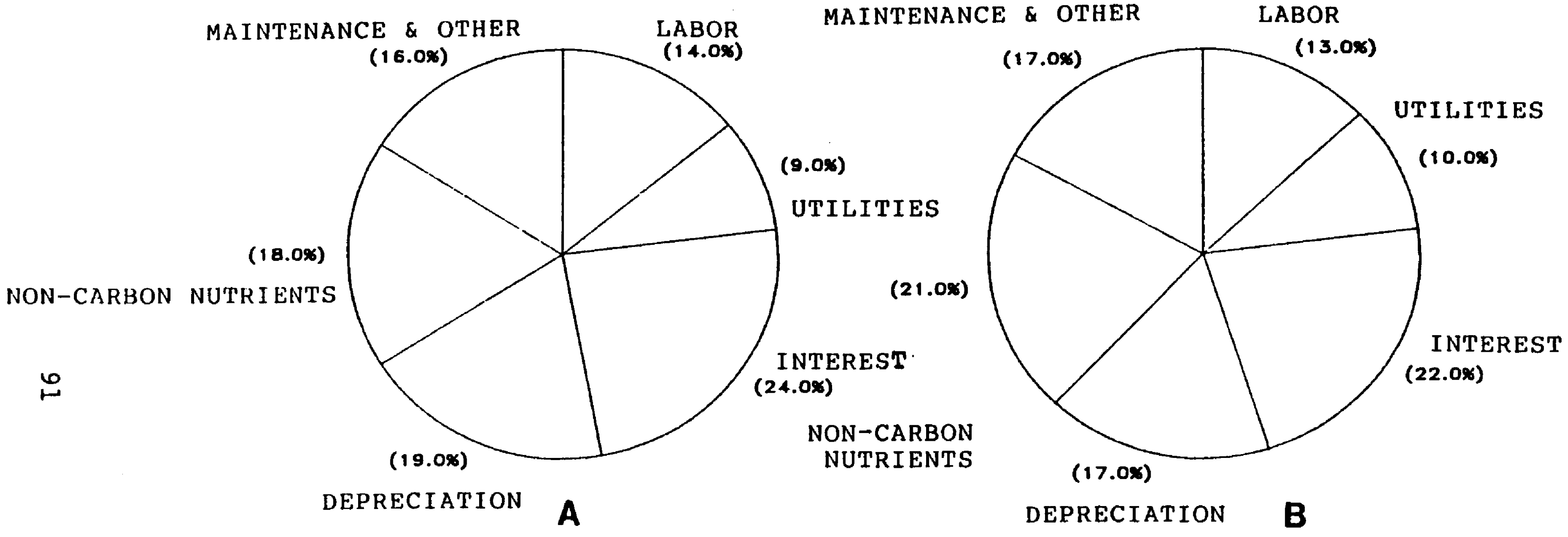

Figure 6-2. Relative contributions to operating costs for baseline (A) and "optimistic" (B) cases, California facility.

Ignore lipid emphasis, conditions and constraint of Southwest

7.0 SCALED EXPERIMENT: FACILITY DESIGN

Task II of this study is to develop a facility design for a scaled experiment to validate the performance and the operating costs expected for a large commercial algae culture facility producing fuels. Emphasis is to be placed on the culture and harvest systems. As is apparent from the preceding discussion, both the biology and the engineering development of the Hawaii-type shallow raceway are still at a rudimentary stage. Many of the engineering parameters have not been optimized (i.e. raceway slope, foil design and placement, CO_2 sump design, settling pond design). The system is intended to be applicable to the U.S. Southwest, but it has not been tested even on a small scale under conditions truly representative of that region; the algal species that might do best in a Southwestern shallow raceway system are unknown. Because of the uncertainty of many design parameters, it is not appropriate to construct large production raceways immediately. The scaled experiment has therefore been broken down into two stages: an initial stage (Stage 1) to test biological and design parameters in a flexible experimental system, and a second stage (Stage 2) in which larger production-scale raceways are built and operated based on the results of the first several Stage 1 experiments. Because the project duration is limited to two years, the two stages overlap.

The design of the scaled experiment rests on the premise that, by the end of the experiment, costs and performance should be sufficiently well known to attract potential private investors to algae culture based on the proposed design. The Stage 2 raceways should therefore be of sufficient scale to estimate realistic construction costs, to demonstrate that algae grows as well in a production-scale raceway as in small experimental ones, and to demonstrate that operation of the raceway system is realistic in terms of labor required for culture operations, harvesting, and maintenance. A true commercial pilot, in which at least several full-sized raceway modules would be constructed and operated and a fuel product would actually be produced in saleable quantities, would require more time (and presumably more funding) than has been allotted by SERI for the scaled experiment. A pilot system would probably be the next step after the scaled experiment and would presumably be privately funded.

Contest premise of Phase II

The experiment is proposed for a Hawaiian site. Besides its proximity to AAI and its subcontractors, a Hawaiian site is highly desirable if significant results are to be achieved in 18 months of experimentation as specified by SERI. The relatively constant conditions in Hawaii and the presence of at least one species that grows well year-round allows a long, consistent series of experiments. This would not be true in the Southwest, where changing seasons would change experimental conditions and where no experiments have yet been done with any species in a shallow raceway system using foils. One would need to select desirable species, a potentially long process since one would have to select at least two species (summer and winter) with both

→ A problem ignored in this proposal

high production rate and easy harvestability. Both species would have to grow well in the particular water type available at the Southwest site. Most of the fastest-growing algae used in Mainland experiments to date are not easy to harvest, and little work has been done on screening algae for high production and solar conversion efficiency under winter conditions. Once suitable species are selected, it is desirable to perform many of the experiments with each species, since they will probably prefer somewhat different culture strategies. Thus, experiments in the Southwest would probably take much longer (perhaps several times as long) in order to model the year-round operation of an algae farm. It is therefore more efficient to conduct the bulk of the optimization experiments in Hawaii, with experiments in the Southwest directed primarily towards species screening for production rate, harvestability, and temperature tolerance in a shallow raceway system. The results from the Hawaii facility should be applicable to algae culture in the Southwest with a minimum of further experimentation.

Harvest? CO_2? temp control? H_2O? recycle

7.1 Site Selection

The Hawaii raceway experiments will be carried out at a site on the western edge of the Barbers Point Naval Air Station near Ewa Beach, Oahu, Hawaii (Figure 7-1). The site was chosen because:

1. It is near the proposed site of the conceptual commercial facility, and provides the same favorable environment for algae culture.

2. It is adjacent to the Hawaiian Independent Refinery, a source of CO_2 large enough to supply the needs of the experimental facility (up to 1 MT/day when all planned raceways are operating). The CO_2 (98% pure) is produced as a byproduct of the refinery's SNG plant. A CO_2 takeoff will be provided at the refinery fence line to supply CO_2 for the experimental facility (R. Fujita, pers. comm.)

3. It is adjacent to an existing drainage ditch which can be used to dispose of the effluent seawater from the facility.

4. The land is available for lease at agricultural rates (D. Rappel, pers. comm.)

Environmental characteristics are essentially the same as those previously described for the conceptual commercial facility: total solar radiation, 4300-5500 kcal/m^2-day, yearly average 5000 kcal/m -day; water salinity (from saltwater wells), 25-30 ppt.

Species screening experiments in the U.S. Southwest will be done at the Roswell Test Facility in Roswell, New Mexico.

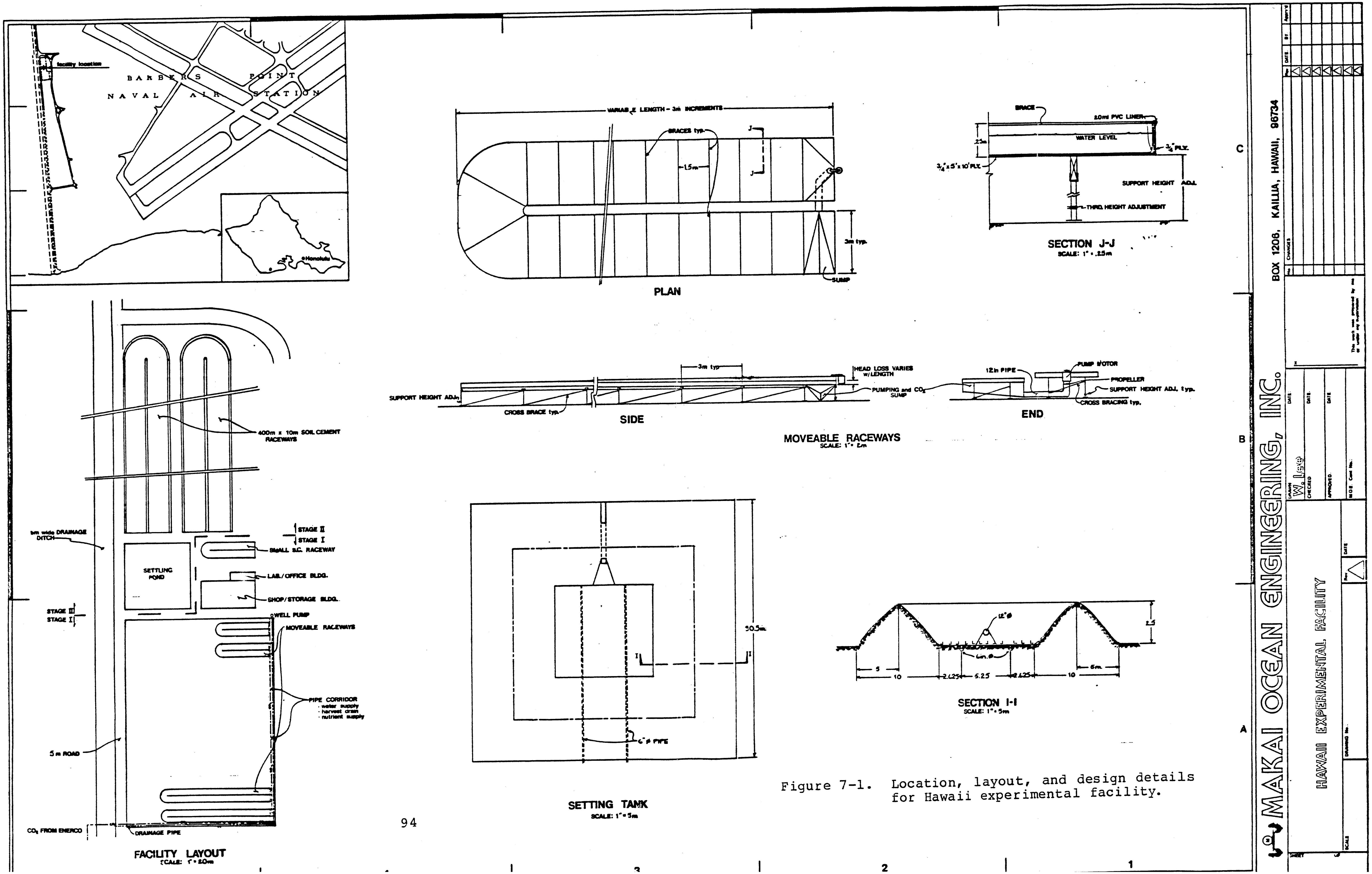

Figure 7-1. Location, layout, and design details for Hawaii experimental facility.

Eastern New Mexico is a candidate region for large-scale algae culture because of a relatively mild climate, availability of saline water, and proximity to geological CO_2 resources (Maxwell et al., 1984). The Roswell Test Facility has the necessary facilities (including saline water at 14 ppt) and analytical equipment already on site. A fuller description of the Roswell Test Facility is given in Appendix 7.

7.2 Facility Design: Stage 1

7.2.1 Raceways

doesn't test feasibility of cement liners proposed for scale up

Most of the Stage 1 experiments will be done in modular aboveground raceways constructed of plywood and lined with vinyl pond liner. The raceways will be built of sections (probably 8' x 10' to conform to readily available lumber sizes and give a 3 m width, which is desirable to avoid significant effects of the raceway sides on head loss). The system offers great flexibility in use; raceway size, number and slope can be varied as desired for each experiment. Enough sections will be provided to build a raceway of 500 m running length in order to provide sufficient length to determine an optimal distance between CO_2 diffusers. This number of sections will be enough (with appropriate end pieces and sumps) to construct as many as 10 50-m running length raceways for experiments to determine the effects of design parameters and operating strategies on production and harvestability of algae (see Section 8.0). Total surface area of the modular raceways will be 1500 m^2. It has been suggested that experimental algae culture ponds should be at least 100 m^2 in area if the results are to be extrapolated to other systems (Benemann et al., 1983). The minimum size of the modular raceways during the scheduled experiments (Section 8.3.2) will be 150 m^2.

In a sloped raceway system, water velocity can be adjusted only by changing the slope, so adjustable raceways are necessary for water velocity experiments. However, the versatility of the sectional raceway system will be helpful in many of the other experiments. The type of pump and the type, number, and locations of CO_2 sumps can be changed readily. The raceways can be moved around the site and even moved to a different site if necessary.

but not performance characteristics

The raceways will sit on adjustable frames on a soil cement pad. The pad is primarily to provide a flat surface for the raceways, but will also provide some idea of the costs and durability of soil cement. Part of the pad will also form the base for a harvest settling pond that can accept harvest water from the experimental raceways in order to validate that the settling pond concept works over larger areas than a 55-gallon drum.

In addition to the modular raceways, one 50-m running length soil cement raceway will be constructed. This raceway will be used to test biocompatibility of the soil cement material with *Platymonas* and to check its durability in a routinely cleaned, flowing seawater system before attempting to construct larger soil cement raceways.

not A good replication for scale verification

7.2.2 Buildings

Two buildings will be required for the experimental facility: a leased office/laboratory trailer and a shop/storage building. The trailer will house analytical equipment, office space, and a small culture room with controlled fluorescent lighting for the maintenance of *Platymonas* stock cultures. It will also contain a computer controller which will monitor and record environmental conditions and control CO_2 and nutrient additions to the raceways. The shop/storage building will contain power tools and shop space to construct the raceway sections, ends, and sumps, to repair raceway components and equipment, and to fabricate other items (such as different foil designs) that are needed for the experiments. It will also be used to store equipment and supplies that cannot be stored outside.

7.2.3 Water Supply and Disposal

30 ppt salinity

Water will be supplied from an 8-10 inch (20-25 cm) diameter well that will be drilled on site. A 90 ft (27 m) deep well should yield water at 25-30 ppt salinity. A 400-gpm (1500 l/min) pump will supply the water to the raceways rapidly enough so that personnel can harvest and fill the whole experimental raceway system within a few hours without disrupting normal operating and monitoring routine or disturbing the 3-day harvest cycle that provides highest yield of *Platymonas* (Laws, 1984).

When not used for algal settling experiments, the effluent water from the raceways will be disposed of through a 6-inch (15-cm) PVC pipe to the drainage channel running along the western side of the site. A pump may be necessary to assist this operation.

7.2.4 Monitoring and Control System

The monitoring and control system will be similar to the one employed at the UH experimental raceway system (Laws et al., 1983). A computer housed in the laboratory trailer will monitor inputs from environmental sensors, record the data at appropriate intervals, and control nutrient inputs to the raceways based on pH measurements. Sensors will include a pH probe with preamplifier in each raceway, a light meter to record daily solar radiation, and a temperature probe in one raceway to monitor water temperature. The computer controller will meter CO_2 (from the main supply line) and nutrients (from storage tanks containing premixed nutrient solutions) into the raceways based on carbon uptake as measured by the pH probes. The amounts of

CO_2 and nutrient solution supplied to each raceway will be recorded by volumetric flowmeters so that utilization efficiencies can be determined. A current meter will be used manually to determine flow rates in the raceways.

7.2.5 Laboratory Equipment

A microscope and hemacytometer will be necessary for daily cell counts to monitor production in the raceways. To filter raceway water samples for total biomass determinations, a filter apparatus and vacuum pump will be needed. An electronic balance (for weighing small samples) and an industrial scale (for weighing larger samples during harvest efficiency studies) will be required. A drying oven and desiccator are required for dry weight determinations, to dry algae samples for CHN analysis, and to store dried samples. A small muffle furnace is needed for ash weight determinations and to precombust filters for CHN samples. A variety of small items and glassware will also be required.

Analyses requiring more expensive equipment, such as nutrient and CHN determinations, will be contracted out to Aecos, Inc., a local environmental services firm, or to Analytical Services at the University of Hawaii.

7.2.6 Additional Equipment

A light truck will be leased to transport materials from Honolulu to the site and for general transportation needs. A small leased forklift will probably be necessary to move heavy materials (such as loads of raceway sections) around the site. Two weeks' rental of a crane and 5 days' rental of a flatbed truck have been included to support construction operations.

A small anaerobic digester has also been included. It will be constructed following a design provided by V. Srivastava of the Institute of Gas Technology in Chicago (Appendix 8). The digester will provide information on the conversion of harvested algae to methane; the volume of gas evolved will be measured and the chemical composition of the digester gas will be analyzed at the HIRI refinery. However, the main function of the digester will be to supply digester effluent (about 60 l/day) for experiments to determine the feasibility of nutrient recycle from an algae-to-methane system. The supernatant liquid will be analyzed to determine what percentage of the input nitrogen and phosphorus can be recovered, and algal production will be measured using digester supernatant as a nutrient source. One week's training at IGT has been budgeted for one individual to learn to operate the digester system properly.

7.3 Facility Design: Stage 2

Can these be calibrated from the modular system?

After the modular raceway experiments have determined design characteristics such as proper pump type, slope/water velocity, head losses, and optimal distance between CO_2 sumps, two large (10 m wide x 400 m running length) soil cement raceways will be designed and constructed. The large raceways will be constructed in essentially the same manner as has been proposed for the conceptual production facility, as modified by the results of Phase 1 experiments. They will be operated as if they were modules of a real production system. Their purpose is to:

1. Test performance of full-width raceways relative to smaller experimental ones.
2. Refine construction cost estimates for large shallow raceways.
3. Determine maintenance requirements: labor, materials, costs.
4. Test culture stability and amount of "downtime".

The large raceways will be about 1/4 the length of the raceways proposed for the conceptual facility, based on the assumption that beyond a certain point, added length will not affect the performance of a raceway.

One settling pond will also be constructed to test the mechanics of settling, draining, and harvesting the algae on a large scale and to determine the actual harvest efficiency and solids content of harvested material from the large raceways. The settling pond will be large enough to accept the harvested water from one large raceway (approx. 350 m^3). The pond should be large enough to allow tests of alternative methods for removing the harvested material (for example, suction harvesting as suggested for the conceptual facility vs. scraping the material into a sump).

The Phase 2 budget proposal (see Section 9.0) may be higher than necessary because it must allow for the many unknowns in raceway design. For example, it assumes that the soil cement must be 10% cement, that the CO_2 sumps must be 4 m deep, and that large amounts of fill must be brought in to construct the large raceways. It is likely that some of these anticipated expenses can be reduced, based on the results of the Phase 1 experiments. The budget is conservative because of the contract requirement to specify the entire project budget now. An alternative funding strategy might be to fund the Phase 1 experiments first, and use the results to plan the Phase 2 budget.

7.4 Facility Design: Southwest Experiments

The experiments at the Roswell Test Facility will be mainly species screening trials to determine those algae (of the ones tried) that give the best production rates in a shallow raceway system under varying environmental conditions. The raceways will not need to be as large or as closely monitored as the Phase 1 experimental raceways. Six raceways about the size of the existing Hawaii raceway (50 m^2) will be constructed. Like the Phase 1 raceways, they will be constructed of plywood and lined, but they will not need to be modular in design.

The Roswell Test Facility is already being used for algae cuture studies, and therefore has most of the additional facilities needed for the species screening studies (B. Goldstein, New Mexico Solar Energy Institute, pers. comm.). An adequate supply of saline water (14 ppt) is available. Inexpensive laboratory space is available for a culture room to maintain cultures of different algae for testing in the raceways. By the time this project is initiated, a computer monitoring system will be on site which can handle the CO_2 input control for the six raceways. Therefore, few other items will be needed except the raceways themselves and the personnel to operate them.

8.0 SCALED EXPERIMENT: OPERATION

8.1 Personnel

Personnel involved in the project will be:

Project Management and Principal Investigators:
Dr. Richard Spencer, AAI
Mr. Frederick Mencher, AAI
Subcontractor (Engineering and Design):
Makai Ocean Engineering
Project Manager (Southwest Site):
Dr. Barry Goldstein, New Mexico Solar Energy Institute
Consultant (Algal Biology):
Dr. Edward Laws, University of Hawaii
Consultant (Economics):
Dr. Karl Samples, University of Hawaii

Four technicians should be sufficient to monitor the Stage 1 experiments, maintain the algal stock cultures, harvest and clean the raceways, and perform the other necessary on-site tasks. Because of the continuous nature of the experiments and the necessity to harvest raceways on a consistent schedule, technicians will be needed on site seven days a week. When the two large raceways are in operation during Stage 2, at least one more technician and possibly two will be required to monitor, clean, and harvest the production raceways. Because of the large amount of light construction work that will be required throughout the project as raceways, sumps, and foil designs are modified, a skilled laborer has been included in addition to the technical personnel. Temporary laborers will be hired as necessary during the construction period and perhaps when the modular raceways are reconfigured.

Two technicians will be required to maintain the species screening experiments in New Mexico.

8.2 Design and Construction

At the beginning of the project, there will be a 5-6 month design and construction period. Included in this time period are the final design and construction of Stage 1 facilities (modular raceways, soil cement pad, small soil cement raceway, buildings, well, etc.). Prior to construction, a soil engineer will be consulted to determine the proper soil cement formulation for the site.

During the design and construction period, several experiments will be done to determine engineering parameters that will be necessary later on. Flume studies will be conducted by MOE personnel at the Look Laboratory of Oceanographic Engineering, University of Hawaii, to determine the actual roughness coefficient of soil cement formulations and the drag produced by various foil designs. These measurements will provide necessary inputs into the design of the large soil cement raceways. Another experiment to be done during the design period is a test of CO_2 sump effectiveness vs. sump depth. A U-tube made of PVC pipe can be used to simulate a sump for this experiment, making the test much easier to do. A CO_2 sparger will be placed in one side of the U-tube. As water flows through the U-tube, some of the CO_2 will dissolve in the water; the amount of inorganic carbon in the water can be measured by measuring pH and alkalinity (S. Smith, University of Hawaii, pers. comm.). The degree of saturation achieved for different sump depths at appropriate water velocities can be compared to the initial design assumptions (Section 3.7). Optimal sump depth is a design criterion for the large Stage 2 raceways and is also important in estimating sump costs for a commercial facility.

8.3 Hawaii Experiments: Stage 1

8.3.1 General Procedures

Initially, the raceway cultures will be started from 20-liter carboy cultures which, in turn, will be started from stock cultures kept in flasks. Once the raceway cultures are established, they are normally quite stable, so it should be possible to run experiments in sequence using the same raceway cultures. A one-week preconditioning period will be allowed between experiments to adapt the cells to new experimental conditions. If a raceway culture does fail, the raceway will be sterilized with dilute sodium hypochlorite solution and seeded from another raceway; the ongoing experiment will be restarted if desired once the new culture is dense enough. If all the cultures fail simultaneously (for example, in a power failure), they can be restarted from carboy cultures.

Every three days, 87% of the water in each raceway will be exchanged. This dilution schedule has proved to enhance growth in the experimental raceway (Laws, 1984).

Based on the present raceway experiments in Hawaii, a two-week production period should be enough to compare treatments in an experiment. Two replicates (raceways) per treatment should be enough to expose significant differences among treatments by analysis of variance, given the reproducibility of production measurements in the existing Hawaii raceways (within about 10%; E. Laws, pers. comm.).

As noted above (Section 7.2.4), CO_2 and other nutrients will be metered into the raceways automatically based on pH measurements by a probe in each raceway. The non-carbon nutrients (nitrogen, phosphorus, and trace metals) will be supplied from small storage tanks containing premixed nutrient solutions. The ratio of non-carbon nutrient input to CO_2 input nothing that isn't done at U. Hawaii

will be determined initially by algal chemical composition but will be refined as utilization efficiencies for the different nutrients become known.

Light intensity will be measured with a Licor LI-1000 light meter and sensor. Raceway water temperature will be determined by a temperature probe in one raceway. The light and temperature measurements will be recorded by the computer controller.

To measure daily algal production, cell counts will be taken daily each morning from each raceway. For a more precise measurement of total production, an aliquot of known volume will be taken from each raceway at the time of harvest. The samples will be filtered on preweighed filters, rinsed to remove salt, and dried to constant weight at 60°C for dry weight measurements. Samples for ash determinations will then be combusted at 500 C for 4 hours. At the end of each experiment, a sample will also be taken from each raceway for CHN analysis to determine carbon and nitrogen content as a proportion of ash-free dry weight. More frequent CHN samples will be taken during experiments testing different fertilizers and fertilization strategies, as these experiments are more likely to produce differences in cell composition among treatments. Proximate analysis will be done occasionally to verify that the proportions of cellular components remain constant, as they do in the existing experimental raceway.

Total production over each 3-day period can be calculated from the dry weight measurements and the areas of the raceways. Production on intermediate days can be estimated from the cell counts. Solar energy conversion efficiency can be calculated from ash-free dry weight and the light measurements. Filtered water samples will be taken from each raceway at harvest for nutrient measurements so that the amount of nitrogen and phosphate lost in the effluent water can be determined. Since the nutrient inputs and algal composition will be known, nutrient utilization efficiencies can be calculated. Unaccounted losses will provide an estimate of nutrient outgassing.

8.3.2 Scheduled Experiments

The following is a list of experiments planned for Phase 1. Most of these experiments do not use the full capacity of the raceways. This is to allow for "down time" of components (broken pumps, leaky liners), to permit reconfiguration for a new experiment while an old one is still going on (cutting turnaround time between experiments), and to allow the freedom to try experiments not in the original plan as new information comes in.

The planned experiments should take 36-45 weeks to complete. In addition, there will be a 1-month "shakedown and calibration period" after the initial construction phase to:

1. test operation of the modular experimental raceways,
2. get the control/monitoring system working,
3. start *Platymonas* carboy cultures, then raceway cultures,
4. set up Experiment 1 raceway configuration.

There will also be at least a two-week period after Experiment 1, after the proper pump type has been determined, when enough pumps for the rest of the experiments are purchased or built. Thus the total time required for the modular raceway experiments will be roughly 42-51 weeks. If the initial design and construction period takes no more than 5-6 months, the modular raceway experiments can be done within 18 months of project startup. Undoubtedly, however, the experiments will raise questions which will require more experiments to answer, so that the modular raceways will be in operation throughout the life of the project.

EXPERIMENT 1: Pump type vs. water velocity

Rationale: The type of pump used may affect the productivity of the algae. Propeller pumps are more efficient than airlifts, but have not been tested on *Platymonas*. This experiment is done first because it determines the type of pump to be used in subsequent experiments.

Water velocity will affect algal productivity and has a strong effect on energy costs. Since the water velocity and the pump type may interact in their effects on the algae, these parameters are tested together.

Duration: 5-8 weeks

designed for Platymonas
but not relevant to other species
necessarily

Experiment 1A: Propeller pumps vs. airlifts at 30 cm/sec

Raceway configuration: 4 100 m running length raceways
2 ea: Propeller pumps with sumps
Airlift pumps with sumps and blower
CO_2 sumps should be separate from pump sumps to avoid outgassing at airlifts
Foils every 1.5 m

Measurements: Production rate/solar conversion efficiency
Energy consumption
Measure electricity consumed by propeller pumps, measure air flow through airlift feed lines
CO_2, N utilization efficiency
Compare outgassing between pump types
Proximate analysis (this is the first chance to measure)

Experiments 1b ... 1n: Same as above but with different velocities. Start with 20 cm/sec, then increase or decrease depending on results.

Note: After Experiment 1 the decision must be made on the preferred pump type for subsequent experiments. Additional pumps are purchased or built following this decision.

EXPERIMENT 2: Foil configuration and spacing

Rationale: Foils are a major cost item in the construction of a Hawaii-type raceway system. A tradeoff must be established between foil spacing (both laterally and along the raceway) and production.

Laws et al. (1983) observed a 120% increase in photosynthetic efficiency in Phaeodactylum using airfoil-shaped structures. With Platymonas, using flat plates, only a 45% increase occurred. While there are many other factors that could account for this difference, it is worth investigating.

→ must do multivariate analysis

Duration: 6 weeks

Raceway configuration: 8 50 m running length raceways
2 raceways ea: Different foil types and/or spacing

Measurements: Production rate/solar conversion efficiency
Head loss: measure pump energy consumption
CO_2, N conversion efficiency: most promising designs only.

Note: Tests of different foil designs and spacings could continue almost indefinitely, especially if potential interactions with water velocity and depth are also explored. No more than 2 or 3 sets of experiments are envisioned before going on to Exp. 4, with additional experiments continuing in "spare" raceways as desired.

EXPERIMENT 3: Distance between CO_2 sumps

Rationale: Distance between CO_2 sumps is a design parameter that must be known in order to design the Stage 2 raceways and to improve capital cost estimates for the conceptual facility. Tradeoffs among CO_2 sump costs, head loss through the sumps, and potential carbon limitation must be made.

Duration: 4-5 weeks

Raceway configuration: 1 500 m running length raceway
CO_2 sumps every 50 m

Measurements: Production rate/solar efficiency with different numbers of CO_2 emitters on
pH vs. distance from CO_2 sumps (measure every 20 m every 2 hrs. during day)
Alkalinity samples together with pH samples will allow calculation of carbon uptake
CO_2 conversion efficiency

EXPERIMENT 4: Acceptability of different fertilizers

Rationale: The conceptual analysis assumes that the least expensive fertilizers will be used, but some of the candidate fertilizers have not been tested on _Platymonas_. They will be tested against fertilizers now in use in the experimental raceway.

Except for iron, trace metal requirements for _Platymonas_ in the raceway have not been demonstrated. This is not a critical cost item, but it is relatively easy to test here.

Duration: 9-12 weeks

Experiment 4a: Nitrogen fertilizers

Raceway configuration: 8 50 m running length raceways
2 ea: ammonia
ammonium sulfate
urea
UAN-32 or other

Measurements: Production rate/solar conversion efficiency
N utilization efficiency
Cell composition, proximate analysis

Experiment 4b: Phosphate fertilizers

Raceway configuration: 6 50 m running length raceways
Use "best" N source from Exp. 6a
2 ea: phosphoric acid
10-34-0
treble superphosphate

Measurements: Production rate/solar conversion efficiency
N, P conversion efficiency
Cell composition

Experiment 4c: Trace metals

Raceway configuration: 8 50 m running length raceways
Use "best" N, P sources from Exp. 6 a & b
2 ea: f/10 metals complete
f/10 without EDTA
f/10 EDTA & Fe without other trace metals
f/10 Fe alone

Measurements: same as 4b

Note: The results of these experiments will dictate whether or not further experiments on fertilizers are desirable.

EXPERIMENT 5: Fertilizer application method

Rationale: If fertilizer can be supplied on an intermittent basis, the nutrient distribution system in a commercial farm can be simplified and perhaps combined with the evaporation makeup water system. This simplification would reduce capital costs. The effectiveness of intermittent fertilization vs. continuous (by demand) fertilization should be tested.

Duration: 3 weeks

Raceway configuration: 8 50 m running length raceways
2 ea: Constant fertilization governed by CO_2 demand
Fertilization at 1-hr intervals
Fertilization at 3-hr intervals
Fertilization at daily intervals

Measurements: as in Exp. 4b; also time series of nutrient samples to examine uptake vs. time

EXPERIMENT 6: Period between cleanings

Rationale: The experimental system is now cleaned every day; daily cleaning would be a significant labor cost for a commercial system. Mechanical cleaning devices will be expensive and will probably require frequent maintenance. When the optimal cleaning frequency is known, it will be much easier to estimate labor requirements for a commercial facility.

Duration: approx. 3 weeks

Raceway configuration: 10 50 m running length raceways
2 ea: cleaned daily
cleaned every 2 days
cleaned every 3 days
cleaned every 6 days
not cleaned

Note: This experiment will be run 3 weeks or until uncleaned raceways exhibit obvious problems.

Measurements: Production rate/solar conversion efficiency
Energy consumption by pump (drag may increase w/o cleaning)

EXPERIMENT 7: Recycle of effluent water

Rationale: Recycle of effluent water is desirable because it reduces total water requirements. In the Southwest, this reduction may be critical; in Hawaii, it would be useful because it reduces effluent loads. The effect of water recycle on production and harvestability in *Platymonas* has not been studied.

Duration: approx. 3 weeks

Raceway configuration: 6 50 m running length raceways
2 ea: Recycle all water after harvest
Recycle 1/2 of water after harvest
No recycle

Measurements: Production rate/solar conversion efficiency
Harvest efficiency: does recycle of unharvested cells reduce future harvests? It may not be possible to answer this question in a short-term experiment.

Then why do it so short a term?

EXPERIMENT 8: Harvestability under different conditions

Rationale: Different environmental conditions and culture strategies may affect settling behavior in _Platymonas_. Harvest efficiency is an important parameter determining the price of algae grown in the conceptual facility. Conditions that produce the greatest harvestability and highest solids content are highly desirable.

Note: Runs concurrently with the other experiments, using harvested material from the experiments.

Configuration: 1 small harvester (55-gallon drum) per experimental raceway - 10 max. Larger experiments done in small settling pond to confirm small-scale efficiencies.

Measurements: Harvest efficiency, solids content of settled material

EXPERIMENT 9: Use of digester effluent as fertilizer

Good idea

Rationale: In a system producing methane as a main product or byproduct, the digester effluent could be a significant source of recycled nutrients. The percentage of nutrients available from this source, and the usefulness to the algae of nutrient-containing compounds in digester effluent are not known.

Duration: 3-5 weeks

Raceway configuration: 4 50-m running length raceways or smaller
2 ea: Digester supernatant + supplemental nutrients
Commercial fertilizer only

Measurements: Nutrient content of digester effluent
Production/solar conversion efficiency
Nutrient utilization efficiency

8.4 Hawaii Experiments: Stage 2

Experiments 1-3 of Phase 1 will establish several design criteria for the large Phase 2 raceways: pump type, raceway slope, depth of CO_2 sumps, distance between CO_2 sumps, and foil design and spacing. Design of the Phase 2 raceways will begin when Experiment 1 ends and will continue until after Experiment 3 ends. When a final design is complete, construction will begin on Phase 2 facilities.

The Phase 2 raceways will be run as production raceways, except for somewhat more thorough monitoring than a production raceway would receive. The raceway cultures will be started with stock material from the smaller Phase 1 raceways. CO_2 input will be monitored and controlled in the same manner as in smaller raceways. Fertilization strategy and cleaning frequency will be determined by the results of the Phase 1 experiments.

Production will be measured in the same way as in the Phase 1 system. CHN, ash, and proximate analyses will be done occasionally as needed to establish the similarity (or difference) of algal composition in large raceways to that in smaller ones, and to determine nutrient utilization efficiencies and solar conversion efficiency in the larger raceways. Energy consumption of the raceway pumps will be recorded. All labor involved in monitoring, cleaning, and maintaining the Phase 2 raceways will be noted. Also noted will be the number of culture failures, if any, and the time it takes to sterilize a raceway and get it back into production.

A variety of devices will be tested as small-scale models of potential cleaning machines.

The Phase 2 settling pond will be large enough to accept the harvest water from one of the large raceways. It will be operated routinely to test Platymonas settling on a large scale over a long period of time so that long-term average harvest efficiency and solids content can be determined. Different strategies for removing settled material from the pond will be compared.

The raceways will be operated until the end of the project, probably 8-12 months. This period of operation will allow reasonably accurate estimates of operating costs and production for a commercial facility.

8.5 Southwest Experiments

The six small raceways at the Roswell Test Facility will be used to screen as many algal species as possible for production and harvestability under varying seasonal conditions. Species will be obtained from the local environment, from the SERI culture collection, and from other research collections. Of particular interest will be other Platymonas species that may exhibit settling behavior like the Hawaiian Platymonas, but are better adapted to Mainland conditions. Relatively large algae are also desirable because they are easier to harvest by screening. The algae will be maintained in the laboratory; several species at a time will be grown out in larger containers to seed the raceways.

→ selection criteria?

Production will be the initial criterion for choosing among species; algae that exhibit the best production during a particular season will be selected for more detailed comparisons of production vs. dilution rate and timing. These parameters have proved critical in obtaining exceptionally high yields in the Hawaii raceway system. The ultimate goal of the Southwest experiments is to define a suite of species that can be cultured successfully in a Southwest U.S. shallow raceway system during different seasons, and thereby to define the potential performance of a shallow raceway culture system in the Southwest.

8.6 Additional Experiments

As noted above (Section 7.2.1), a small soil cement raceway will be operated during Phase 1 to test biocompatibility and durability of soil cement under operating conditions before the large soil cement raceways are designed. After this experiment ends, the raceway will be sprayed with Parabond for a test of biocompatibility of this product. An anaerobic digester will be built mainly for nutrient recycling studies, but will also be monitored for gas production, gas composition (analysis will be done by HIRI refinery staff), and energy consumption (heating and stirring of digester contents).

Experiments testing the use of unharvested algae as feed for shellfish have not been listed because of SERI's mandate as an energy research institute, although byproducts such as shellfish could contribute substantially to the economics of an algae fuels facility. AAI intends to pursue shellfish culture experiments on its own using raceway and settling pond effluents that are not needed for other purposes.

Other experiments (such as trials with other species) will be done at SERI request.

The computer economic model will be refined throughout the contract period based on the results of the experiments.

A schedule of the proposed series of experiments is shown in Figure 8-1.

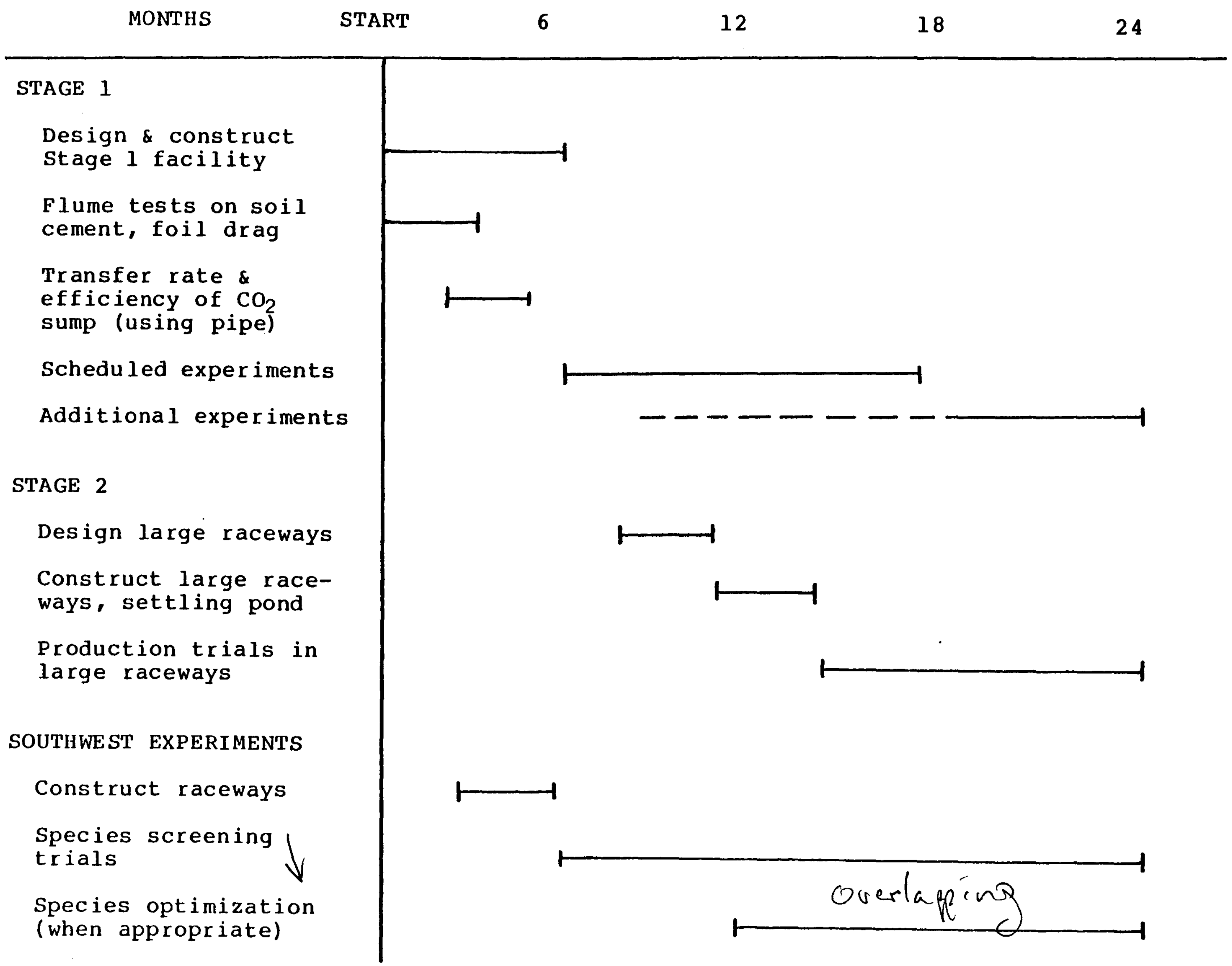

Figure 8-1. Schedule of proposed experiments.

9.0 PROPOSED BUDGET

Cost Estimate for Microalgae Experiment

All prices include installation unless labor costs are specified

Stage 1 Cost Estimate

Item	Total Cost	Quanity	Unts	Unit Costs	Source	Description
Moveable Raceways (10')		328.0				
Supports metal 10'spcg	$16,262.00	346.0		$47.00	Atlas Sales	Scaffolding type framewk, adjstable 2.5-3.5 ft
Plywood	$16,375.00	500.0	ea	$32.75	Honsador	Plywood, 328 sheets for base of rcwy, rest for sides
2x6x10' support	$5,929.00	1,078.0	ea	$5.50	Oahu Lumber	2x6x10 ft beams under plywood
Liner total FOB Hono	$35,100.00	97,500.0	sqft	$0.36	Staff Ind	20 mil pvc liner, enough for relining 6 times
H2O/CO2 Sumps	$5,955.00	10.0	ea	$595.50	MOE	Wood for H2O/CO2 sumps+pipe for U tubes
Fasteners & misc.	$6,358.28				MOE	
Circulation Pumps	$10,980.00	12.0	ea	$915.00	MOE	Special design prop. pumps or airlifts
Foils, Matl + Assby	$12,500.00	6,250.0	ea	$2.00	MOE	5086 aluminum
Assbly labor(on above)	$72,054.78	2,401.8	hrs	$30.00	MOE	Assembly approx. equals cost of materials
Subtotal	$181,514.05					with extra compensation for skilled tradesmen
Sea Water supply						
Well, drill & etc	$15,750.00	90.0	ea	$175.00	Roscoe-Moss	1 Well 8-10 in dia, 90 ft deep
Pump	$7,500.00	1.0	ea	$7,500.00	Roscoe-Moss	400 gpm cast iron pump, 20' head, installed
Pipe, Ftgs & Valves &	$18,085.25	1.0	ea	$18,085.25	MOE	600 ft 6in. pipe, 11-50 ft x 4in hose installed
Subtotal	$41,335.25					
Harvesting equipment						
Pump	$5,000.00	1.0	ea	$5,000.00	MOE	Discharge pump to trench
Hose & pipe	$10,860.60	1.0	ea	$10,860.60	MOE	600' 6 in pipe, 11 x 50' 4 in pipe, 'T's & connectors
Small Settling Pond	$3,100.00	2.0	ea	$1,550.00	MOE	1 small settling pond(3.5 m Dia) + valves, piping
Digestors	$10,000.00	1.0	ea	$10,000.00	Inst.Gas Tech.	15 gal/day (effluent) digestor
Training trip (IGT)	$4,000.00	1.0	ea	$4,000.00	I.G.T.	
Subtotal	$32,960.60					
Nutrients						
Mixing tanks	$2,000.00	4.0	ea	$500.00	MOE	Tanks for mixing fertilizers
Pump	$500.00	1.0	ea	$500.00	MOE	0.25 gpm pump, for nut.
Feeding pipe & ftgs &	$2,052.75	1.0	ea	$2,052.75	MOE	600' 1/2 inch pipe, connectors, tees
Subtotal	$4,552.75					
Computer						
Hardware	$10,000.00	1.0	ea	$10,000.00	MOE	computer w/A to D sampling
Wiring	$12,000.00	1.0	ea	$12,000.00	MOE	
Software/Interface	$6,000.00	1.0	ea	$6,000.00	MOE	Program dev., interface, calibration, debugging & data
CO2 Diffuser	$726.00	132.0	ft	$5.50	Mulvilhill	11 x 10 ft of Plastipor tubing
CO2 Meter volume	$16,500.00	11.0	ea	$1,500.00	Signet Sci.	
CO2 Cntrl Valves	$2,750.00	11.0	ea	$250.00	Signet Sci.	
Ph probe + amp	$5,500.00	11.0	ea	$500.00	Signet Sci.	
Nutrient meter	$5,500.00	11.0	ea	$500.00	Signet Sci.	
Nutrient Cntrl Valves	$5,500.00	11.0	ea	$500.00	Signet Sci.	
Light meter	$1,500.00	1.0	ea	$1,500.00	Licor	
Temperature	$200.00	1.0	ea	$200.00	MOE	
Velocity meter	$1,500.00	1.0	ea	$1,500.00	MOE	
Subtotal	$67,676.00					

High data collection costs

Buildings						
Office/lab	$15,900.00	1.0	ea	$15,900.00	Mokulua Cnsltnt	10' x 32'
Storage/Shop	$14,400.00	1,600.0	ft2	$9.00	Tectonics	20'x80' Metal storage structure
Concrete slab for shop	$4,938.27	19.8	cuyd	$250.00	MOE	Floor slab for storage building
Subtotal	$36,738.27					
Lab, Shop & Office eqpt						
Surveyor's Transit	$500.00	1.0	ea	$500.00	MOE	
pH meter	$1,500.00	1.0	ea	$1,500.00		
Microscope	$2,000.00	1.0	ea	$2,000.00	Haw. Chem	
Hemacytometer	$75.00	1.0	ea	$75.00	Curtin-Matheson	
Glassware	$1,000.00	1.0	ea	$1,000.00	AAI	
Vacuum Pump+fltr	$500.00	1.0	ea	$500.00	Cole-Palmer	
Electronic Balance	$600.00	1.0	ea	$600.00	Cole-Palmer	
Industrial Scale	$1,700.00	1.0	ea	$1,700.00	Cole-Palmer	
Drying Oven	$1,050.00	1.0	ea	$1,050.00	Cole-Palmer	
Muffle Furnace	$450.00	1.0	ea	$450.00	Cole-Palmer	
Desiccator	$40.00	1.0	ea	$40.00	Cole-Palmer	
Freezer	$300.00	1.0	ea	$300.00	Sears	
Wattmeter	$300.00	1.0	ea	$300.00	MOE	
Shop supplies	$15,000.00	1.0	ea	$15,000.00	MOE	Power Saws, Plumbing Tools, Hand Tools, Block & Tackle,
Word Processor	$5,000.00	1.0	ea	$5,000.00	AAI	
Subtotal	$30,015.00					
Electrical Instl	$16,600.00	1.0	ea	$16,600.00	MOE	$10000 matls and 40 hrs electrician
Earthwork Stg 1	w/labor					
Mobilization	$5,000.00	1.0	ea	$5,000.00		
Clear & Grub	$25,200.00	2.1	acre	$12,000.00	St. Soil Serv.	Clear and Minimum Hauling
Survey	$1,320.00	2.0	crw/d	$660.00	NCE	2-3 men/crew
Fill	$19,035.00	1,269.0	cuyd	$15.00	MOE & HD&C	6 in. on pad, slpe+berms sm rcwy
Spreading Fill	$761.40	1,269.0	cuyd	$0.60	NCE p167	small rcwy & Pad
Grading	$11,737.50	78,250.0	sqft	$0.15	NCE p168	small rcwy & Pad
Supervision	$10,200.00				MOE	1 mo engineer & 1 mo foreman
Soil Analysis	$1,500.00	1.0	ea	$1,500.00	Soils Int.	Gene Shinsato, Soils Engineer analysis for Soil cement
Soil-Cement mat'l	$40,927.95	272.9	tons	$150.00	HD&C	4 in. sm rcwy + 6 in. pad, 10% cmt
instl	$35,212.50	78,250.0	sqft	$0.45	3x HD&C	
H20/CO2 Sumps dig	$1,320.00	110.0	cuyd	$12.00	MOE	
concrete	$6,566.00	13.4	cuyd	$490.00	MOE	
pump	$10,000.00	1.0	ea	$10,000.00	MOE	1710 gpm, 2-3 ft head pump (2 hp) for sml rcwy
CO2 Delivery to site	$12,000.00	1.0	ea	$12,000.00	NCE	800 ft pvc, buried, 100 ft stl buried, blower,valve,met
Dist. on site	$2,500.00	500.0	ea	$5.00	NCE	500 ft 2inch pvc instld
Subtotal	$183,280.35					
Subtotal Stage 1	$594,672.27					
Indirect						
G & A (5%)	$30,236.11					
Fee (10%)	$60,472.23					
Excise Tax (4%)	$27,817.22					
Total Stage 1	$723,247.83					

New Mexico Experiment						
Equipment						
Raceways	$9,750.00	6.0	ea	$1,625.00	MOE	6-50 m2 plywood raceways w/20 mil pvc liners
Pumps & Pipes	$4,800.00	6.0	ea	$800.00	MOE	6 propellor pumps and required piping
Monitoring Eqpt	$5,000.00	1.0		$5,000.00	AAI	pH probes, control valves and misc. monitoring eqpt
Foils	$450.00	180.0	ea	$2.50	MOE	Plastic foil arrays
Subtotal	$20,000.00					
Operating Costs						
CO2, Nutrients & Elec	$20,000.00	2.0	yr	$10,000.00	AAI	
Rent	$400.00	2.0	yr	$200.00	AAI	
Misc. Supplies	$2,000.00	2.0	yr	$1,000.00	AAI	
Travel	$26,000.00	20.0	trip	$1,300.00	AAI	10 Trips to New Mexico site per year
Labor						
Site Manager	$12,000.00	24.0	man-m	$500.00	AAI	Barry Goldstein
Technicians	$96,000.00	48.0	man-m	$2,000.00	AAI	2 Technicians for two years
Subtotal	$156,400.00					
Subtotal for New Mexico	$176,400.00					
G & A (5%)	$8,220.00					
Fee (10%)	$17,640.00					
Excise Tax (4%)	$8,090.40					
Total for New Mexico	$210,350.40	+ 700 AAT				
Stage 2 Cost Estimate						
Earthwork ph 2	w/labor					
Mobilization	$5,000.00	1.0	ea	$5,000.00		
Clear & Grub	$60,000.00	5.0	acre	$12,000.00	St. Soil Serv.	Clear and Minimum Hauling
Survey	$1,320.00	2.0	crw/d	$660.00	NCE	2-3 men/crew
Fill	$90,825.00	6,055.0	cuyd	$15.00	MOE & HD&C	6 in. on slpe+berms lg rcwy & Settling pond
Spreading Fill	$3,633.00	6,055.0	cuyd	$0.60	NCE p167	2 lg rcwys + settling pond
Grading	$36,515.63	243,437.5	sqft	$0.15	NCE p168	2 lg rcwys + settling pond
Supervision	$15,300.00				MOE	1.5 mo engr & 1.5 mo frmn
Soil-Cement mat'l	$66,281.80	441.9	tons	$150.00	HD&C	4 in. 2 lg rcwy + 6 in. pond, 10% cmt
instl	$109,546.88	243,437.5	sqft	$0.45	3x HD&C	
H20/CO2 Sumps dig	$3,960.00	330.0	cuyd	$12.00	MOE	4 m deep
concrete	$15,680.00	32.0	cuyd	$490.00	MOE	4 m deep
Pumps	$51,172.00	2.0	ea	$25,586.00	M & W Pump	5000 gpm, 5 ft hd (10 hp)
Valves & Piping	$6,080.00	2.0	ea	$3,040.00	Fresno V. & Apa	2x50' of 12 in, 1 valve at 500, 45' of 16 in
CO2 Sumps dig	$12,744.00	1,062.0	cuyd	$12.00	MOE	6 sumps at 4 m deep
concrete	$50,568.00	103.2	cuyd	$490.00	MOE	6 sumps at 4 m deep
diffuser	$1,452.00	264.0	ft	$5.50	Mulvilhill	8 x 33 ft of Plastipor tubing
Settling Pond						
Drain pipe	$2,361.60	295.2	ft	$8.00	MOE	3-6 in Dia PVC 30 m long
Valves	$1,800.00	3.0	ea	$600.00	Fresno Valve	3-Line Gate or Canal valves
Aluminum Ch.	$259.78	288.6	ft	$0.90	Ducommun Metal	288 ft of 1x1 in Al. angle
Harvest Mach(Dsgn Exp)	$10,000.00	1.0	ea	$10,000.00	MOE	Mat'l for various Machines to harvest slurry
Pump(Effluent Rcycl)	$4,000.00	1.0	ea	$4,000.00	NCE	800 gpm, 10ft head for recycling effluent wateer from s
Subtotal	$548,499.68					
Foils Matl + Assbly	$26,666.67	13,333.3	ea	$2.00	Ducommun & MOE	20 cm w.r.t. width, 1.5 m w.r.t. Length
Installation	$6,666.67	13,333.3	ea	$0.50	MOE	1 man 30/hr @ $15/hr
Subtotal	$33,333.33					

Clning Mach.(Dsgn Exp.)	$15,000.00	1.0	ea	$15,000.00	MOE	Mat'l for various Machines to clean lg raceways
Meters & Valves						
CO2 Meter Volume	$3,000.00	2.0	ea	$1,500.00		
Ph probe + amp	$1,500.00	3.0	ea	$500.00		
Nutrient meter	$1,000.00	2.0	ea	$500.00		
Control Valves for Nut	$1,000.00	2.0	ea	$500.00		
Subtotal	$6,500.00					
Subtotal Stage 2	$603,333.01					
Indirect						
G & A (5%)	$30,166.65					
Fee (10%)	$60,333.30					
Excise Tax (4%)	$27,753.32					
Total Stage 2	$721,586.28 + 1,000,000 Stg 1					
Total Hawaii Project Operating Costs (24 months)						
Operating Costs						
Land Rental	$3,000.00	15.0	ac/yr	$200.00	AAI	
Electricity	$34,214.40	15,840.0	kwh/m	$0.12	MOE	22 Kw for 24 hrs for 30 days for 18 mos
Nutrients	$24,500.00	1.0	ea	$24,500.00	PRI	400kg/day afdw for 6 mos, 60 MT/yr N Fertilizer + P Fer
CO2	$6,930.00	252.0	MT	$27.50	PRI	.4 MT/day for 1 yr(lg rcwy) & .3 MT/day for 1 yr(smalle
Contract Lab Anal.	$10,000.00				AAI	
Travel	$4,000.00	4.0	trips	$1,000.00	AAI	2 trips/yr to SERI
Vehicles						
Light truck	$8,100.00	18.0	mnth	$450.00	Auto & Eqmnt Leasing + amr Insurace est	
Leased Crane	$3,300.00	1.0	mnth	$3,300.00	Bacon 14 ton	
Leased Forklift	$21,600.00	18.0	mnth	$1,200.00	Rent Monthly from Bacon 4 ton	
Flatbed Rental	$2,200.00	5.0	day	$440.00		
Labor						
Engineering						
Dsgn & Supervision	$50,000.00	10.0	man-m	$5,000.00	MOE	2 eng'rs for 2 mos for design & const. supervision
Experimentation	$30,000.00	6.0	man-m	$5,000.00	MOE	1 eng'rs for 2 mos for clning & harvesting Machine desi
Admin/Scientists	$97,500.00	30.0	man-m	$3,250.00	AAI	Rick Spencer and Fred Mencher, AAI
Consultant(Ed Laws)	$6,000.00	24.0	man-m	$250.00	E.L.	Parttime consultation with Ed Laws
Consultant(K. Samples	$3,000.00	24.0	man-m	$125.00	K.S.	Parttime consultation with project economist
Secretary	$36,000.00	24.0	man-m	$1,500.00	AAI	1 fulltime secretary
Technicians	$240,000.00	96.0	man-m	$2,500.00	AAI	6 fulltime technicians for 12 mos
Skilled Labor	$90,000.00	18.0	man-m	$5,000.00	MOE	1 Skilled laborer for 12 mos
Gen'l labor	$86,400.00	72.0	man-m	$1,200.00	MOE	4 temporary hire laborers for 12 months
Total Operating Costs	$756,744.40					
G & A (5%)	$33,387.22					
Fee (10%)	$75,674.44					
Excise Tax (4%)	$34,632.24					
Total Hawaii Oper. Cost	$900,438.30					
Grand Total(Haw+N.Mex)	$2,555,622.81 Wow					

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APPENDIX A

Parameter Test for Laws Shallow Raceway

PARAMETER TEST FOR LAWS SHALLOW WATER RACEWAY

Prepared for:

Aquaculture Associates

Prepared by:

Makai Ocean Engineering, Inc.

November 14, 1984

PARAMETER TEST FOR LAWS SHALLOW WATER RACEWAY
DRAFT

INTRODUCTION

The object of this study was to determine the importance of several physical parameters characteristic of Laws' shallow raceway system to the power consumption and head loss associated with water circulation around these raceways. The parameters investigated in this study were:

1. Raceway water depth
2. Raceway width
3. Raceway length
4. Water velocity
5. Bottom surface roughness (friction factor)
6. Circulation pump efficiency
7. Mixing foils
    a. Drag coefficient
    b. Distance between foil sections

THE COMPUTER MODEL

The open channel flow theory and the exact equations used in calculating power consumption and head loss are presented in the Appendix of this report. To incorporate these equations into a raceway model it was assumed that there were no bends in the raceway, that the raceway was of rectangular cross-section and that the mixing foil arrays were of a shape and size consistent with those currently in Laws' raceways. The computer model allows circulation power per unit acre or head loss per 100 meters to be plotted versus any of the above listed parameters. The importance of a given parameter was tested by varying its value over a given range and calculating the power consumption or head loss at each increment. The range over which each parameter was tested was governed by practical considerations, by a desire to adhere to Ed Laws' basic system and by a desire to evaluate the effects of extreme parameter values. A baseline case which partially corresponded to Laws' system parameters appears on each plot as a reference. The parameters that make up this baseline case are listed below:

1. Depth = 10 cm
2. Width = 10 m
3. Velocity = 30 cm/sec
4. Bottom surface roughness, N = 0.01 m^(1/6) (Smooth concrete)
5. Pump efficiency = 80%

For those plots that include hydrodynamic parameters the baseline values are:

6. Foil angle (relative to horizontal) = 20°
7. Distance between foil sections = 1.5 m

A plot of power consumption or head loss versus a given parameter was the output from the program. Figure 1 is a sample of the plots that make up the output; it illustrates the change in power consumption with a variation in velocity. Note in Figure 1 that a second parameter is also varied in steps to obtain a spread of curves and that the baseline case mentioned above corresponds to the Eff = 80%" characteristic. The spread of curves allows the relative importance of each parameter to be better evaluated. For example in Figure 1 it is clear that a small increase in velocity has a greater affect on power consumption than a small increase in efficiency. To translate power consumption curves into operating costs one can assume that 1 watt per acre would cost $1.00/year to supply based on $.12/KWH electrical costs.

Hydrodynamic drag losses resulting from the addition of foil sections in the raceways were included late in this study. The foil sections were assumed to be flat plates of the same dimensions as those currently in use in Laws' raceways. These flat plates are designed for use at a 10cm water depth, so assuming use of this same size foil in a deeper raceway would be inaccurate since it probably would not induce a high enough level of turbulence and mixing to achieve Laws' production rates. The drag coefficient for a flat plate inclined to the flow direction is strongly related to the angle of inclination of the plate. The two parameters which relate to hydrodynamic head loss and power consumption which were tested in this study are the foil angle of inclination (represents drag coefficient) and the spacing between foil sections down the running length of the raceway.

RESULTS

The results of this study are a number of plots of power per unit acre and head loss per 100 meters versus each of the parameters mentioned above. Each parameter has a characteristic curve shape associated with it. Beginning with the power consumption curves Figures 2 through 11 give an indication of these characteristic shapes and the importance of each parameter with respect to power consumption.

Figure 2 illustrates the cubic relationship between velocity and power consumption. This cubic function translates into a very rapid rise in power consumption for any increase in velocity above 0.1 m/s. As in Figure 1 the variation of width shown in Figure 2 has a much smaller effect on power consumption than a variation in velocity.

Figure 3 shows the square relationship between friction factor and power consumption. This square function does not cause as rapid nor as sudden an increase in power consumption as the cubic characteristic shown in Figure 2. However, it appears that a small change in friction factor is more important than a small

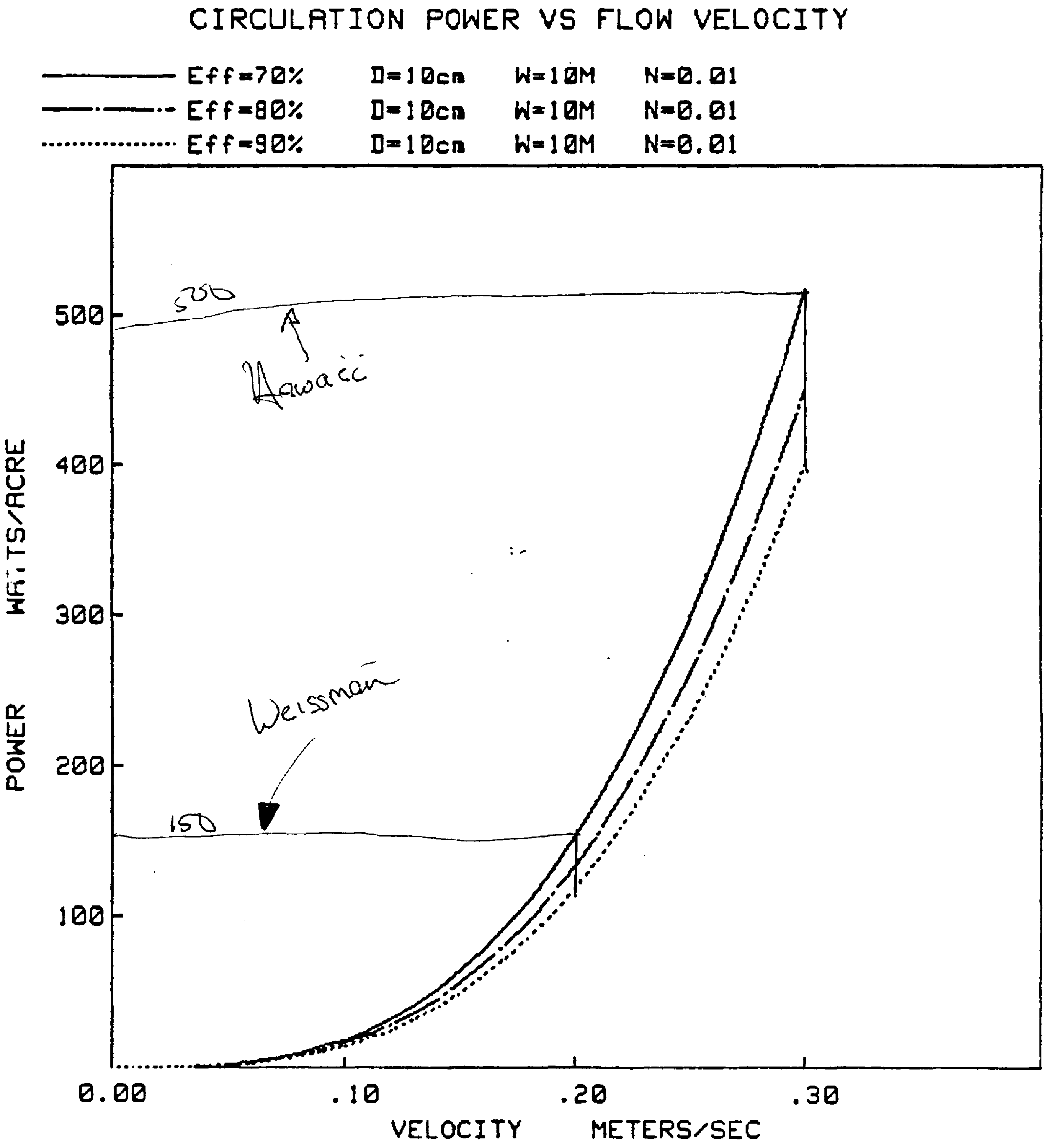

CIRCULATION POWER VS FLOW VELOCITY
Eff=70% D=10cm W=10M N=0.01
Eff=80% D=10cm W=10M N=0.01
Eff=90% D=10cm W=10M N=0.01
POWER WATTS/ACRE
500
400
300
200
100
0.00
.10
.20
.30
VELOCITY METERS/SEC
500
Hawaii
Weissman
150

Figure 1

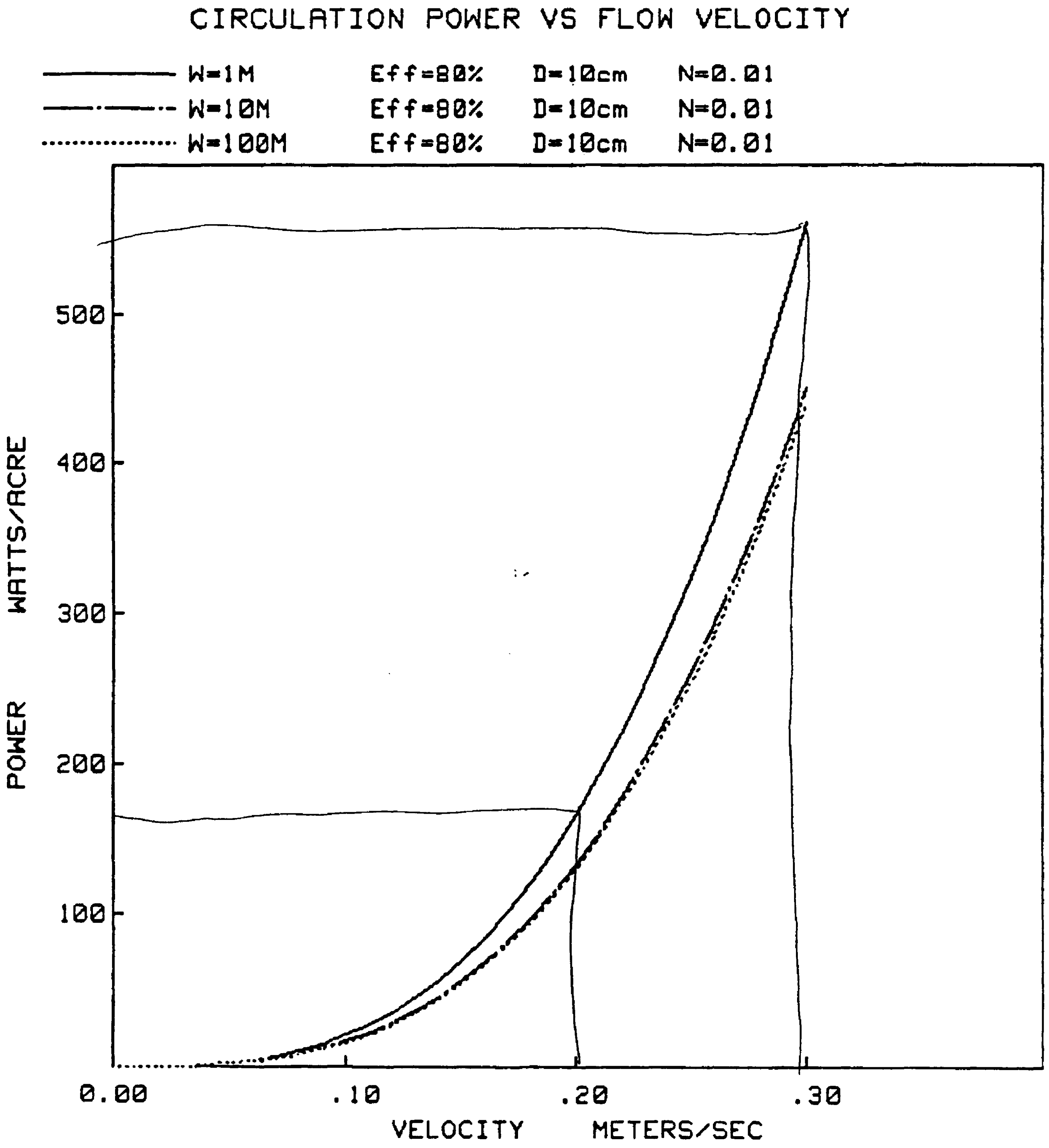

CIRCULATION POWER VS FLOW VELOCITY
W=1M Eff=80% D=10cm N=0.01
W=10M Eff=80% D=10cm N=0.01
W=100M Eff=80% D=10cm N=0.01
POWER WATTS/ACRE
500
400
300
200
100
0.00
.10
.20
.30
VELOCITY METERS/SEC

Figure 2

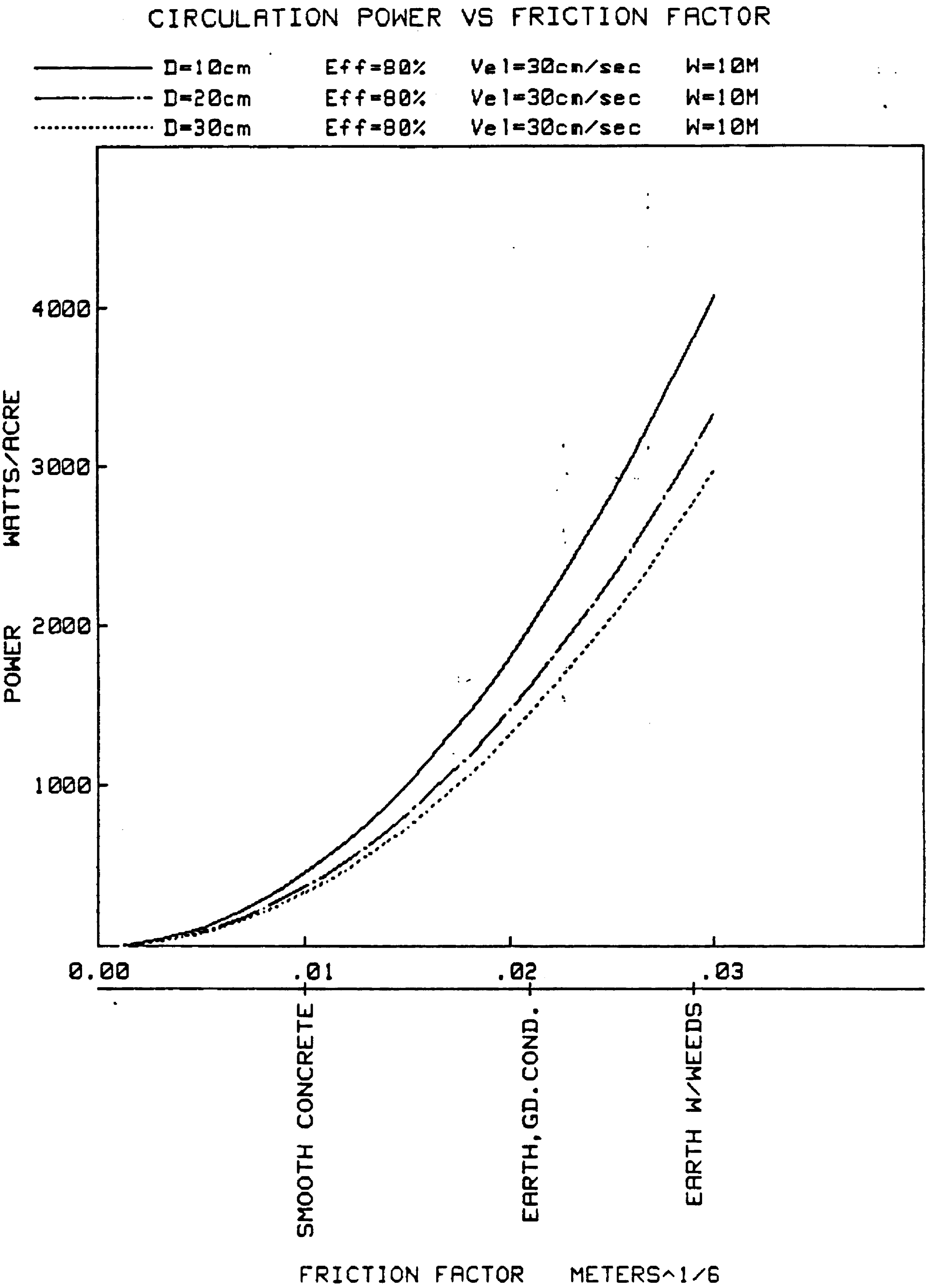

CIRCULATION POWER VS FRICTION FACTOR
D=10cm Eff=80% Vel=30cm/sec W=10M
D=20cm Eff=80% Vel=30cm/sec W=10M
D=30cm Eff=80% Vel=30cm/sec W=10M
POWER WATTS/ACRE
4000
3000
2000
1000
0.00
.01
.02
.03
SMOOTH CONCRETE
EARTH, GD. COND.
EARTH W/WEEDS
FRICTION FACTOR METERS^1/6

Figure 3

change in depth. Note that a second horizontal axis has been plotted on this figure, and the friction factors of three potential raceway building materials is shown relative to the friction factor scale.

Figure 4 is a plot of power consumption versus width at various raceway flow velocities. This curve is essentially flat except at relatively small raceway widths. Note that this figure is the inverse of Figure 2 as the parameters being varied have been reversed. The importance of flow velocity over raceway width is more vividly illustrated in figure 4 than in Figure 2.

In Figure 5 we look at the characteristic curve of power consumption versus raceway depth at various pump efficiencies. In this curve the power consumption becomes greatest when the depth is very small and decreases as the depth increases. At shallow depths a change in depth will have a greater effect on power consumption than a change in pump efficiency. At deeper depths the opposite is true, and for depths approximating the depth of Laws' raceways, a determination of which parameter is of greater importance is difficult to make from this figure.

The characteristic curve for power versus circulation pump efficiency is shown in Figure 6. The same curve plotted over a smaller range of interest is shown in Figure 7. Efficiency is inversely proportional to pumping power. Therefore, at relatively low efficiencies a given efficiency improvement means a large improvement in power consumption. However, continued efficiency improvements of the same magnitude lead to gradually diminishing returns. Note also from Figure 7 that velocity reduction is of more importance than efficiency improvement in reducing power consumption.

Two figures are used to illustrate the relationship between pond length and power consumption. Figure 8 is a plot of actual power consumption versus raceway length at various water depths. Actual power is linearly related to length; changing depths changes the slope of this linear relation. Figure 9 is the result of plotting power consumption per acre versus length. In this case raceway length no longer has an influence on power consumption and drops from consideration as an important parameter.

Figure 10 illustrates the square relationship between power consumption and foil angle of inclination at various flow velocities. As foil angle goes to zero the curve approaches a minimum value for power consumption offset from the horizontal axis. This minimum power value corresponds to the power required to overcome drag due to raceway bottom friction. Note that changes in velocity affect both the minimum power consumption point of each curve and the shape of the power versus foil angle square curve.

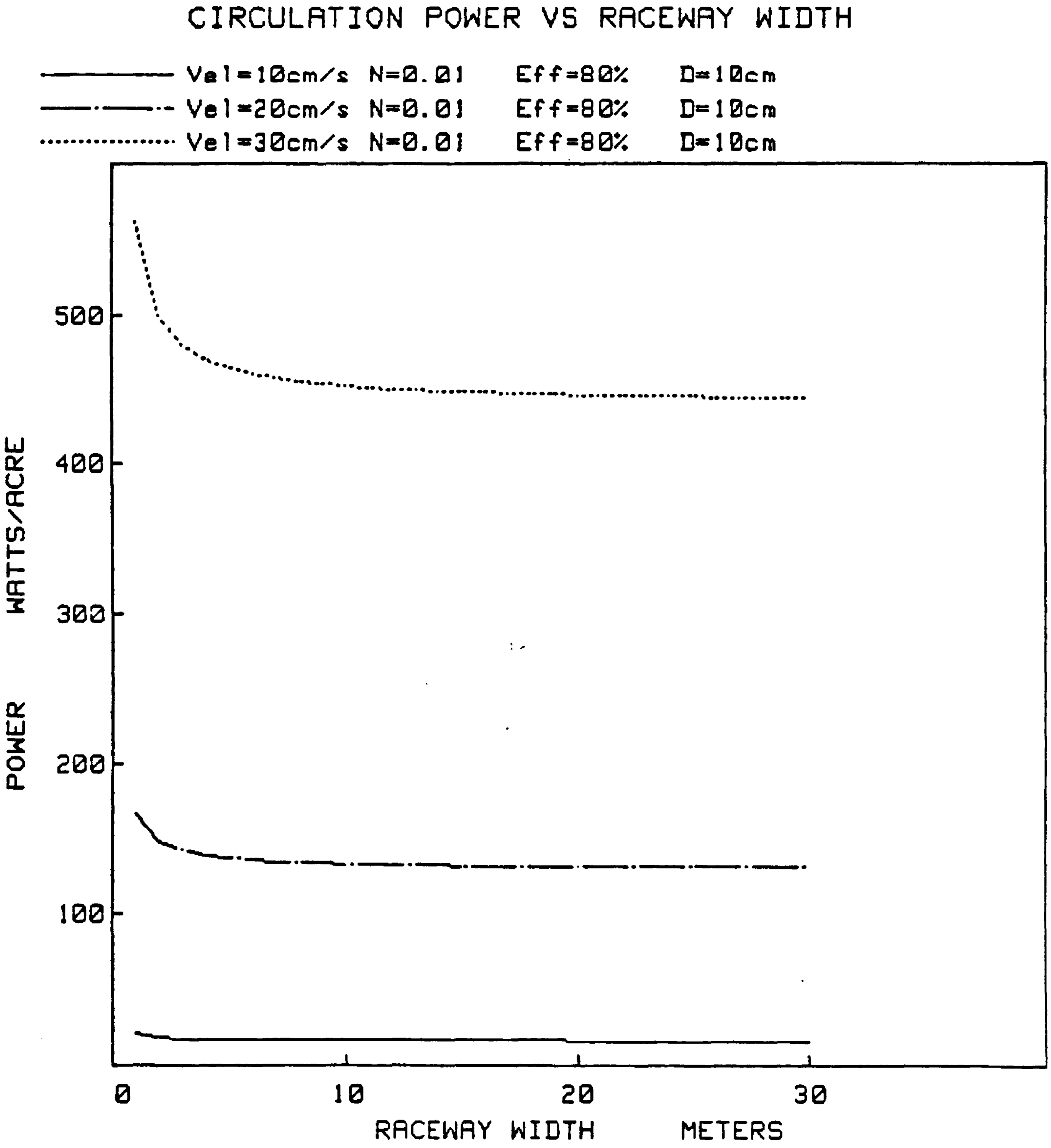

CIRCULATION POWER VS RACEWAY WIDTH
Vel=10cm/s N=0.01 Eff=80% D=10cm
Vel=20cm/s N=0.01 Eff=80% D=10cm
Vel=30cm/s N=0.01 Eff=80% D=10cm
POWER WATTS/ACRE
100
200
300
400
500
0
10
20
30
RACEWAY WIDTH METERS

Figure 4

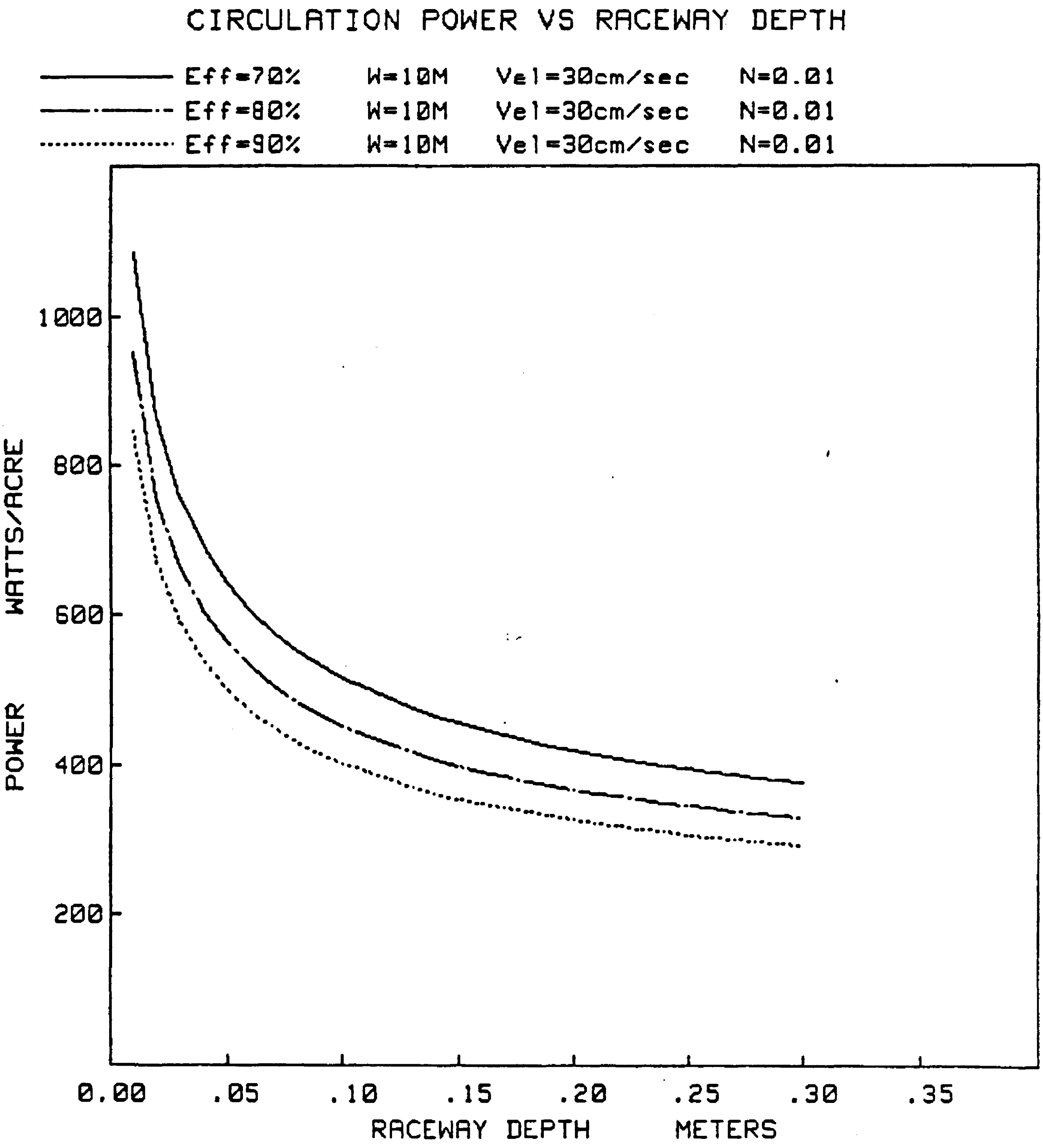

CIRCULATION POWER VS RACEWAY DEPTH
Eff=70% W=10M Vel=30cm/sec N=0.01
Eff=80% W=10M Vel=30cm/sec N=0.01
Eff=90% W=10M Vel=30cm/sec N=0.01
POWER WATTS/ACRE
1000
800
600
400
200
0.00
.05
.10
.15
.20
.25
.30
.35
RACEWAY DEPTH METERS

Figure 5

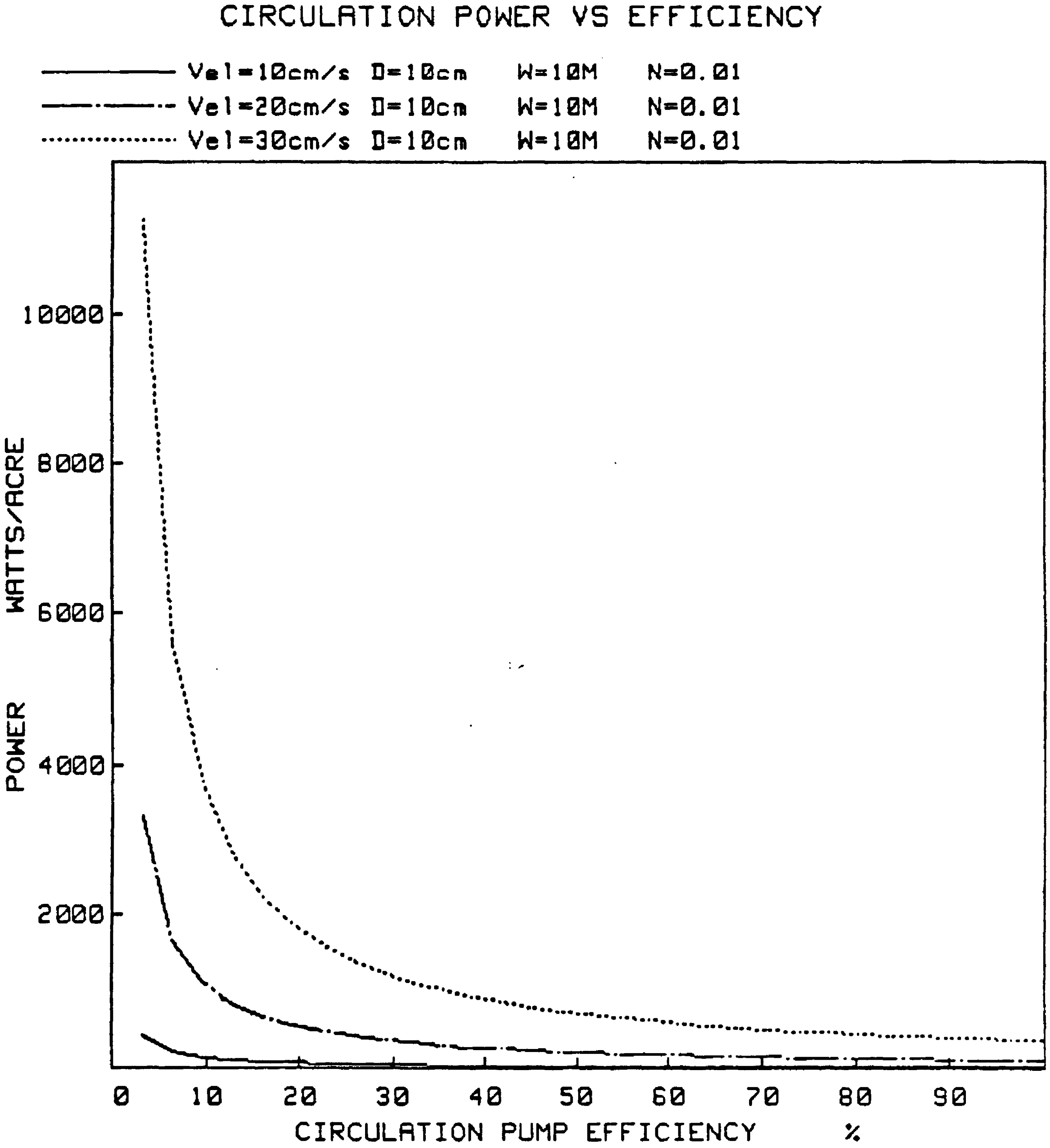

CIRCULATION POWER VS EFFICIENCY
Vel=10cm/s D=10cm W=10M N=0.01
Vel=20cm/s D=10cm W=10M N=0.01
Vel=30cm/s D=10cm W=10M N=0.01
POWER WATTS/ACRE
10000
8000
6000
4000
2000
0
10
20
30
40
50
60
70
80
90
CIRCULATION PUMP EFFICIENCY %

Figure 6

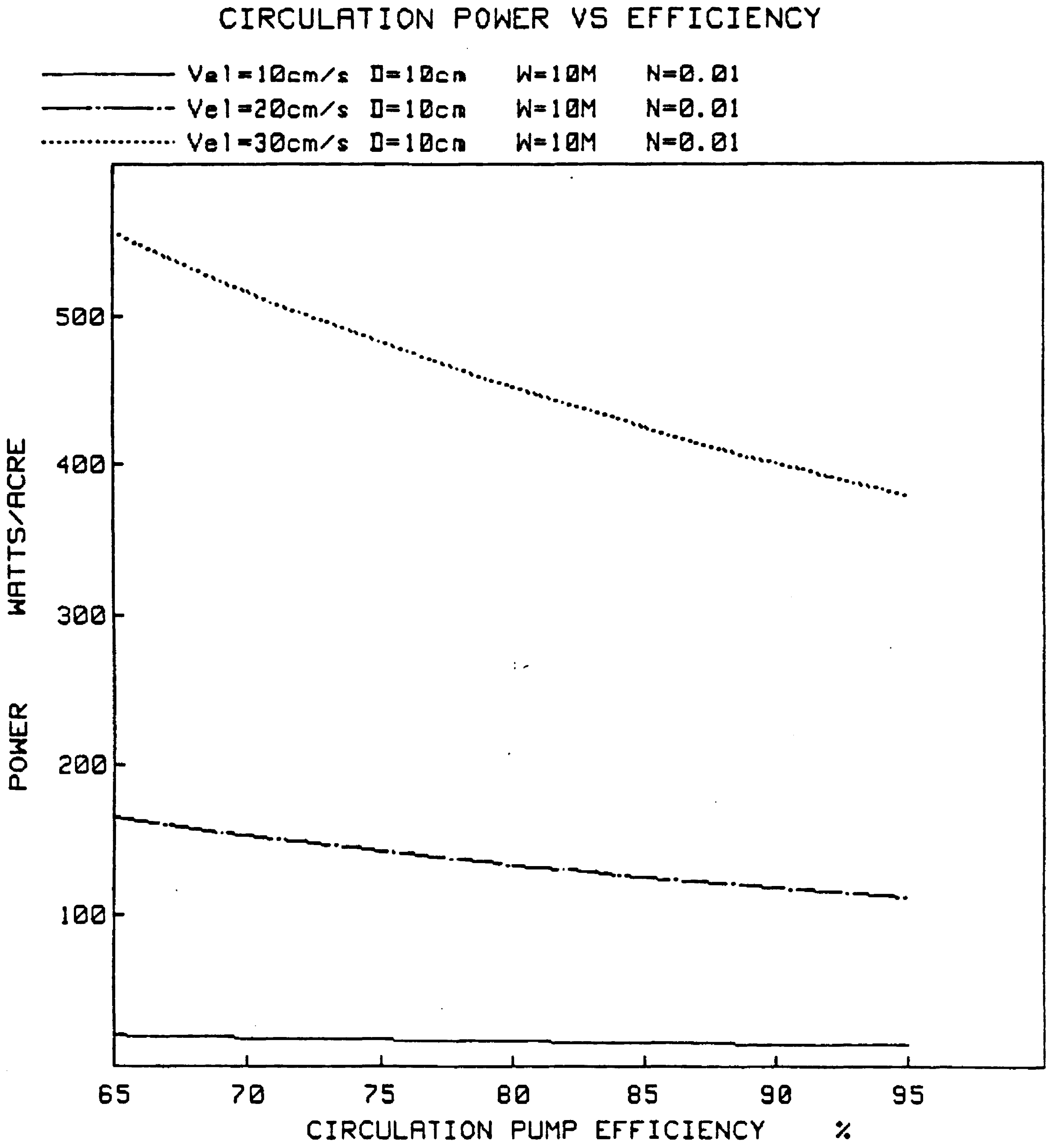

CIRCULATION POWER VS EFFICIENCY
Vel=10cm/s D=10cm W=10M N=0.01
Vel=20cm/s D=10cm W=10M N=0.01
Vel=30cm/s D=10cm W=10M N=0.01
500
400
300
200
100
POWER WATTS/ACRE
65
70
75
80
85
90
95
CIRCULATION PUMP EFFICIENCY %

Figure 7

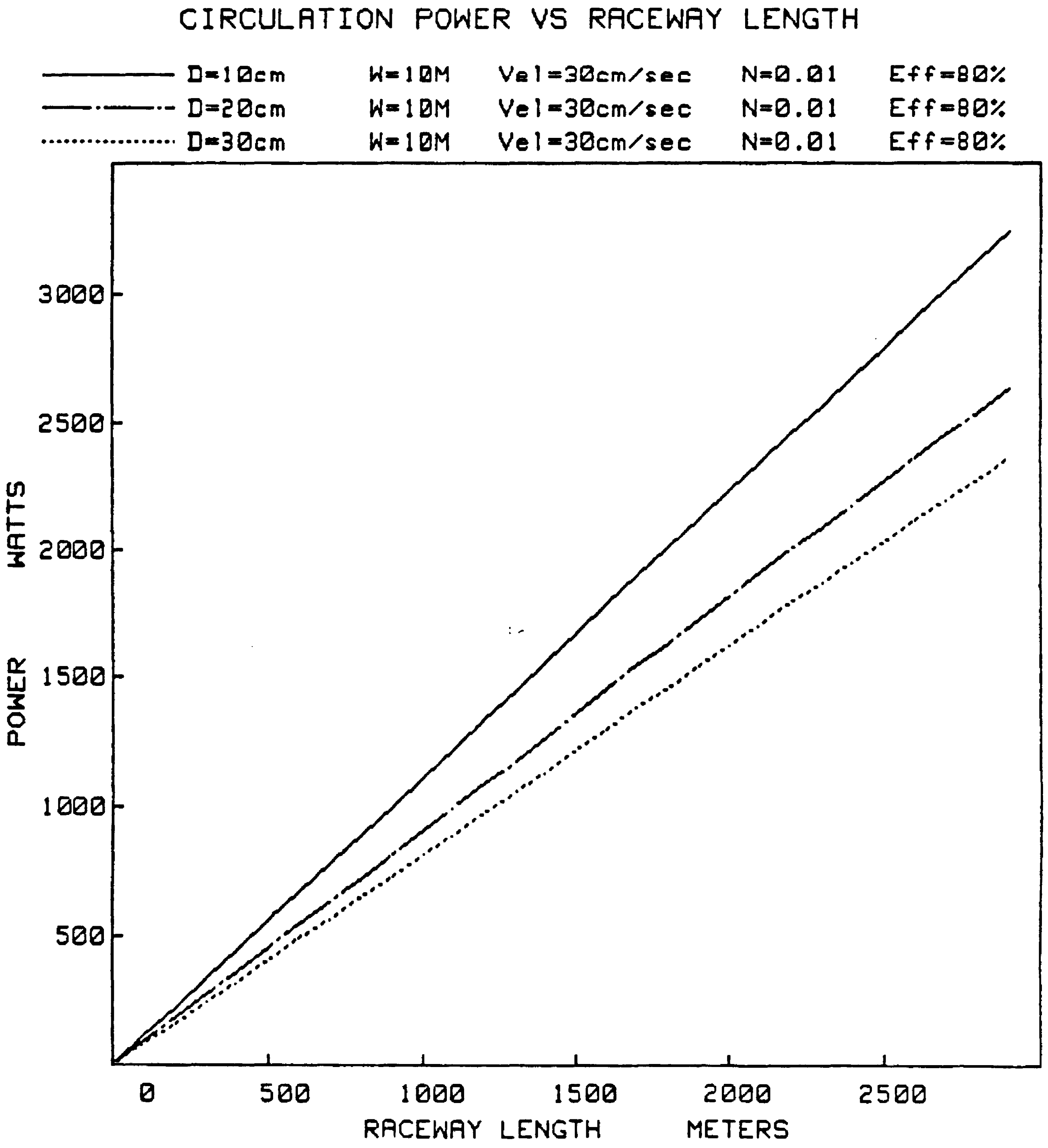

CIRCULATION POWER VS RACEWAY LENGTH
D=10cm W=10M Vel=30cm/sec N=0.01 Eff=80%
D=20cm W=10M Vel=30cm/sec N=0.01 Eff=80%
D=30cm W=10M Vel=30cm/sec N=0.01 Eff=80%
POWER WATTS
3000
2500
2000
1500
1000
500
0
500
1000
1500
2000
2500
RACEWAY LENGTH METERS

Figure 8

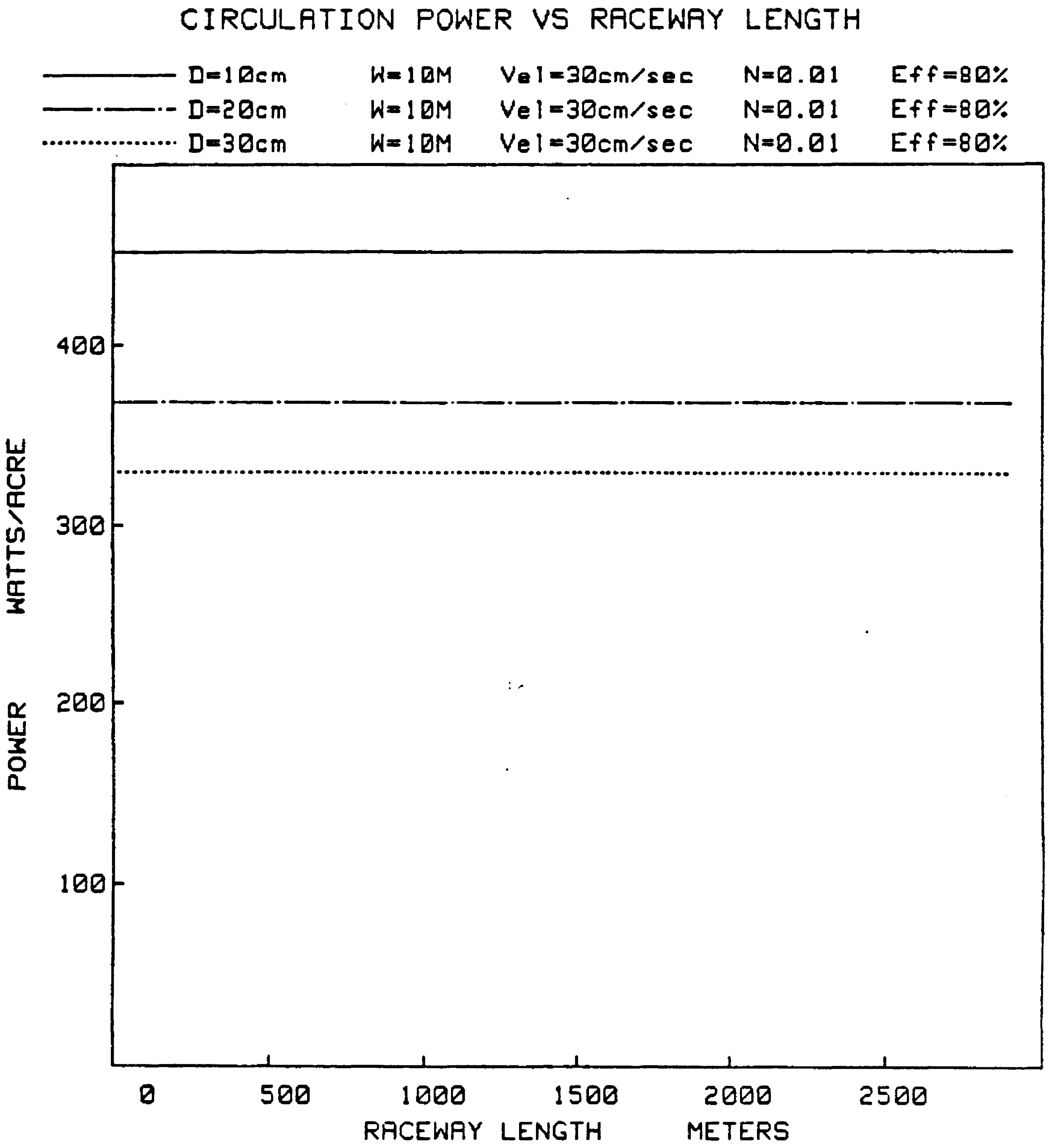

CIRCULATION POWER VS RACEWAY LENGTH
D=10cm W=10M Vel=30cm/sec N=0.01 Eff=80%
D=20cm W=10M Vel=30cm/sec N=0.01 Eff=80%
D=30cm W=10M Vel=30cm/sec N=0.01 Eff=80%
POWER WATTS/ACRE
100
200
300
400
0
500
1000
1500
2000
2500
RACEWAY LENGTH METERS

Figure 9

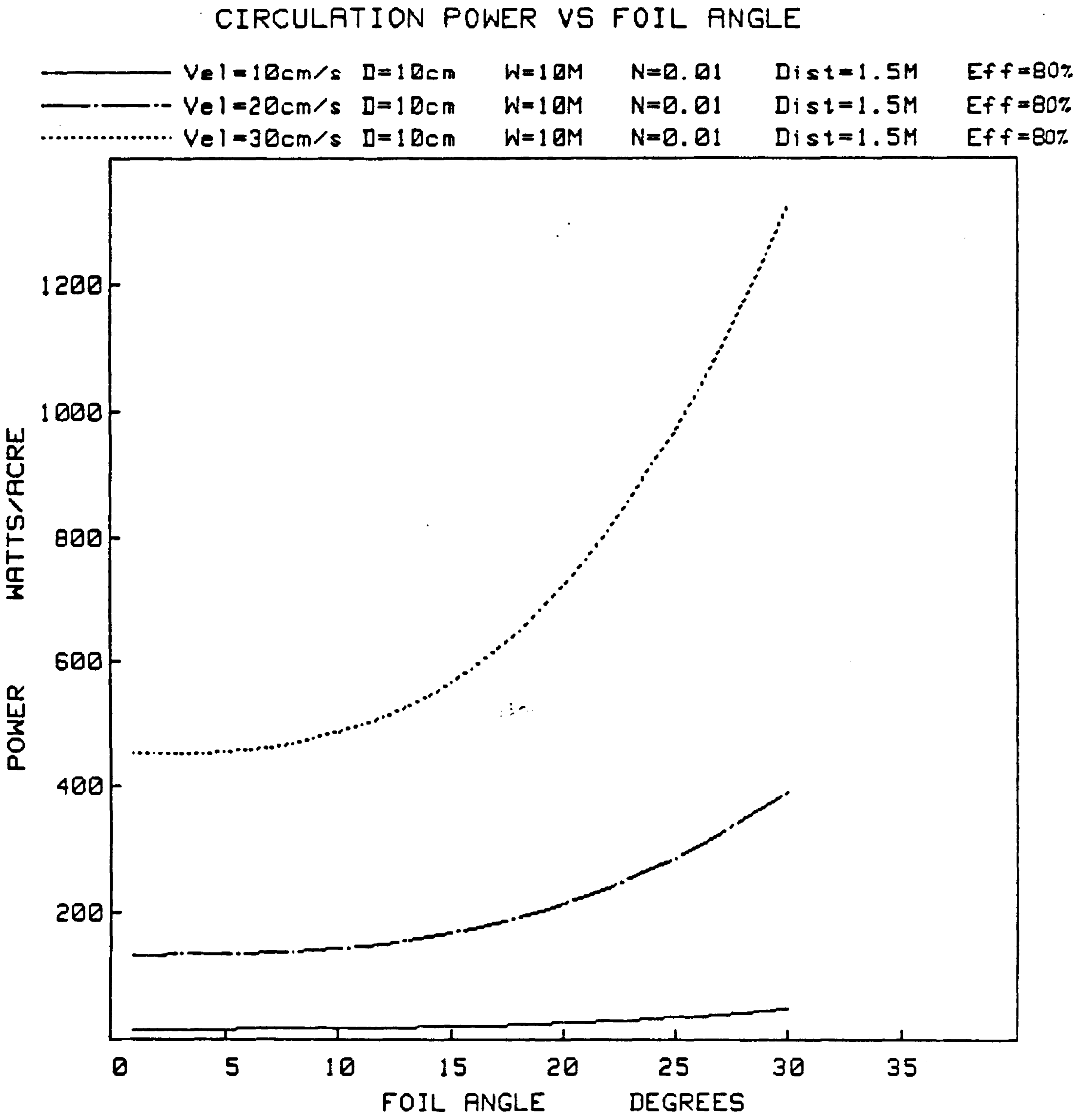

CIRCULATION POWER VS FOIL ANGLE
Vel=10cm/s D=10cm W=10M N=0.01 Dist=1.5M Eff=80%
Vel=20cm/s D=10cm W=10M N=0.01 Dist=1.5M Eff=80%
Vel=30cm/s D=10cm W=10M N=0.01 Dist=1.5M Eff=80%
POWER WATTS/ACRE
200
400
600
800
1000
1200
0
5
10
15
20
25
30
35
FOIL ANGLE DEGREES

Figure 10

The characteristic curves for power consumption versus distance between foil sections are shown in Figure 11. Power is inversely proportional to the distance between foil sections, but a minimum value for power consumption exists that is approached as the distance between foils becomes very great. Since this is an inverse proportional relationship as was the case with pump efficiency, increasing the distance between foil sections by a given increment will initially lead to large power reductions. However, a continued increase in spacing by this same increment will lead to diminishing returns. Note that changing the friction factor, N, has no influence on the shape of the curves in Figure 11, but only affects the distance from the horizontal axis that the curves are offset.

Characteristic curves for head loss versus the parameters tested in this study do not vary from those described above for power consumption with the exception of flow velocity. Head loss is proportional to the velocity squared, as shown in Figure 12. This means that head loss does not change as rapidly nor as suddenly with velocity variation as does power consumption. A sampling of other head loss plots are contained in the Appendix of this report.

There are several interesting iteractions between parameters in this study which deserve further discussion. The two parameters which have the greatest influence on both head loss and power consumption are flow velocity and friction factor. By varying these two parameters together a worst case and best case for power consumption and head loss can be generated which is relatively independent of the values for the other parameters tested. Figures 13 through 15 illustrate this trend and show how these parameters can combine to form worst case power consumption curves, i.e. N=0.03m (1/6). Figures 16 through 18 demonstrate how these same two parameters can generate best case power consumption curves, i.e. Vel=10cm/s, essentially independent of the other parameters tested. Reduction of both flow velocity and friction factor will be extremely important to the achievement of a low power consumption raceways system.

The interdependence of raceway depth and width is shown in Figure 18. The most interesting feature about the spread of curves shown in Figure 18 is the rise in power consumption for depths greater than 0.1 m and W=1 m versus the drop in power consumption over this same depth range for the W=10 m and W=100 m characteristics. Closer examination of Figure 20, which shows these same parameters inverted, reveals that to obtain this desirable power reduction and head loss with increasing depth the raceway width must be at least 30 times larger than raceway width. For a nominal raceway depth of 10cm, the minimum raceway width will be 3 meters.

The dependence of the foil angle characteristic curve on flow velocity has already been mentioned (Figure 10). Flow velocity is the most important parameter in increasing both the friction and drag components of the circulation power equation and head loss equation. Reduction in velocity will cut the friction losses between the raceway bottom surface and the moving water and the drag force exerted by the foil sections on the water. Figure 21 and 22 dramatically illustrate the head loss reduction and power reduction with any decrease in velocity.

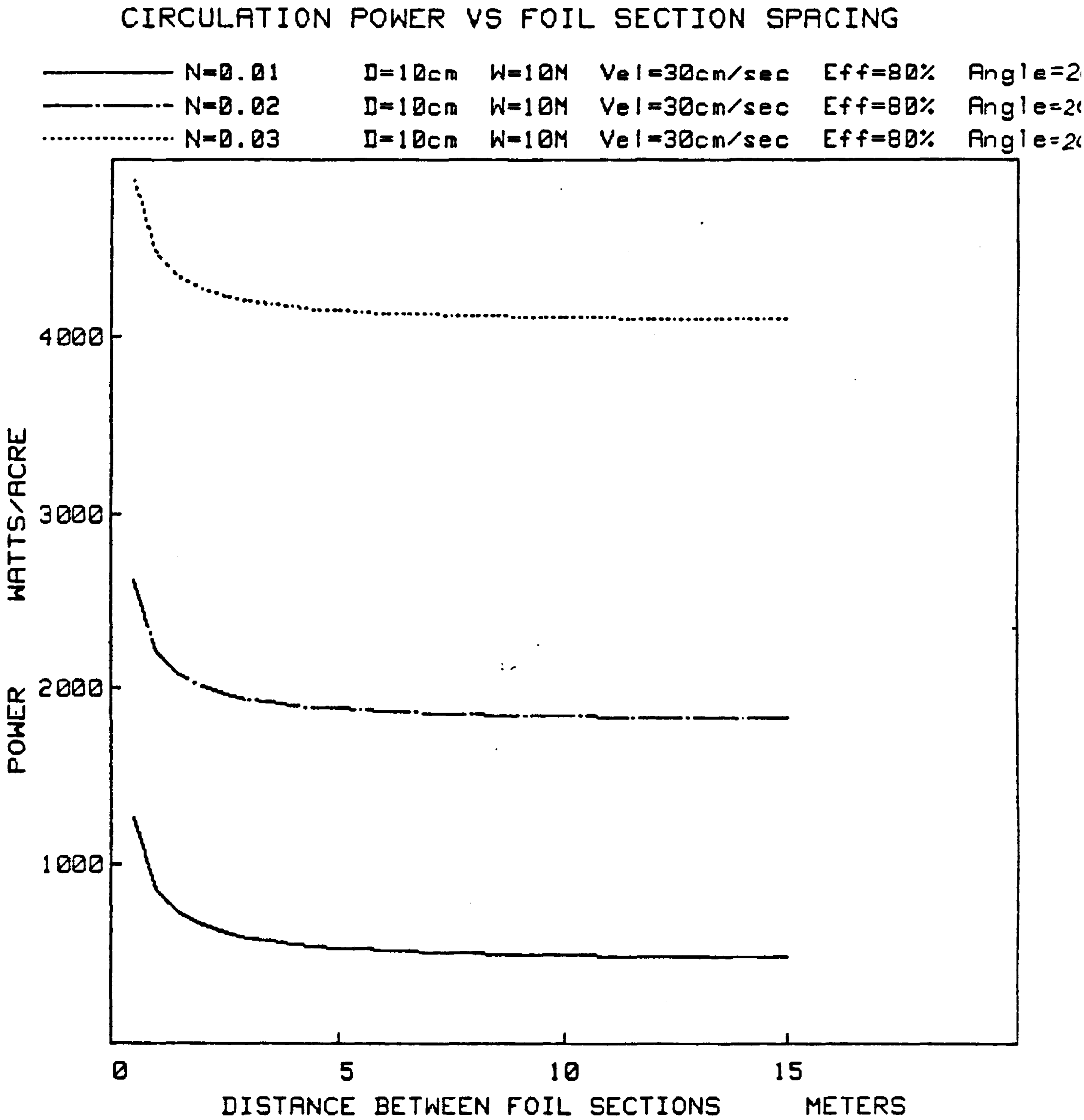

CIRCULATION POWER VS FOIL SECTION SPACING
N=0.01 D=10cm W=10M Vel=30cm/sec Eff=80% Angle=2
N=0.02 D=10cm W=10M Vel=30cm/sec Eff=80% Angle=2
N=0.03 D=10cm W=10M Vel=30cm/sec Eff=80% Angle=2
POWER WATTS/ACRE
4000
3000
2000
1000
0
5
10
15
DISTANCE BETWEEN FOIL SECTIONS METERS

Figure 11

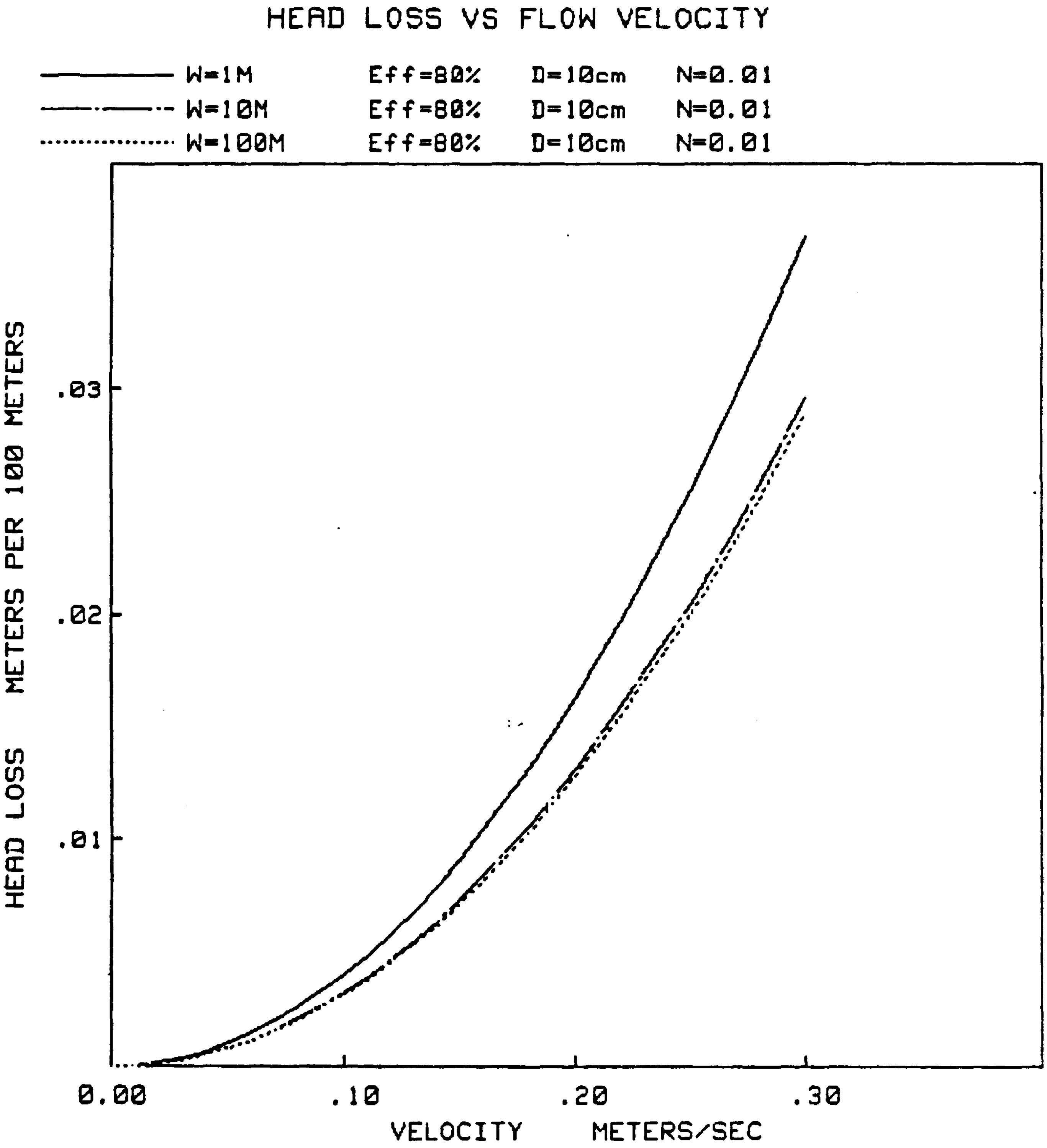

HEAD LOSS VS FLOW VELOCITY
W=1M Eff=80% D=10cm N=0.01
W=10M Eff=80% D=10cm N=0.01
W=100M Eff=80% D=10cm N=0.01
HEAD LOSS METERS PER 100 METERS
.01
.02
.03
0.00
.10
.20
.30
VELOCITY METERS/SEC

Figure 12

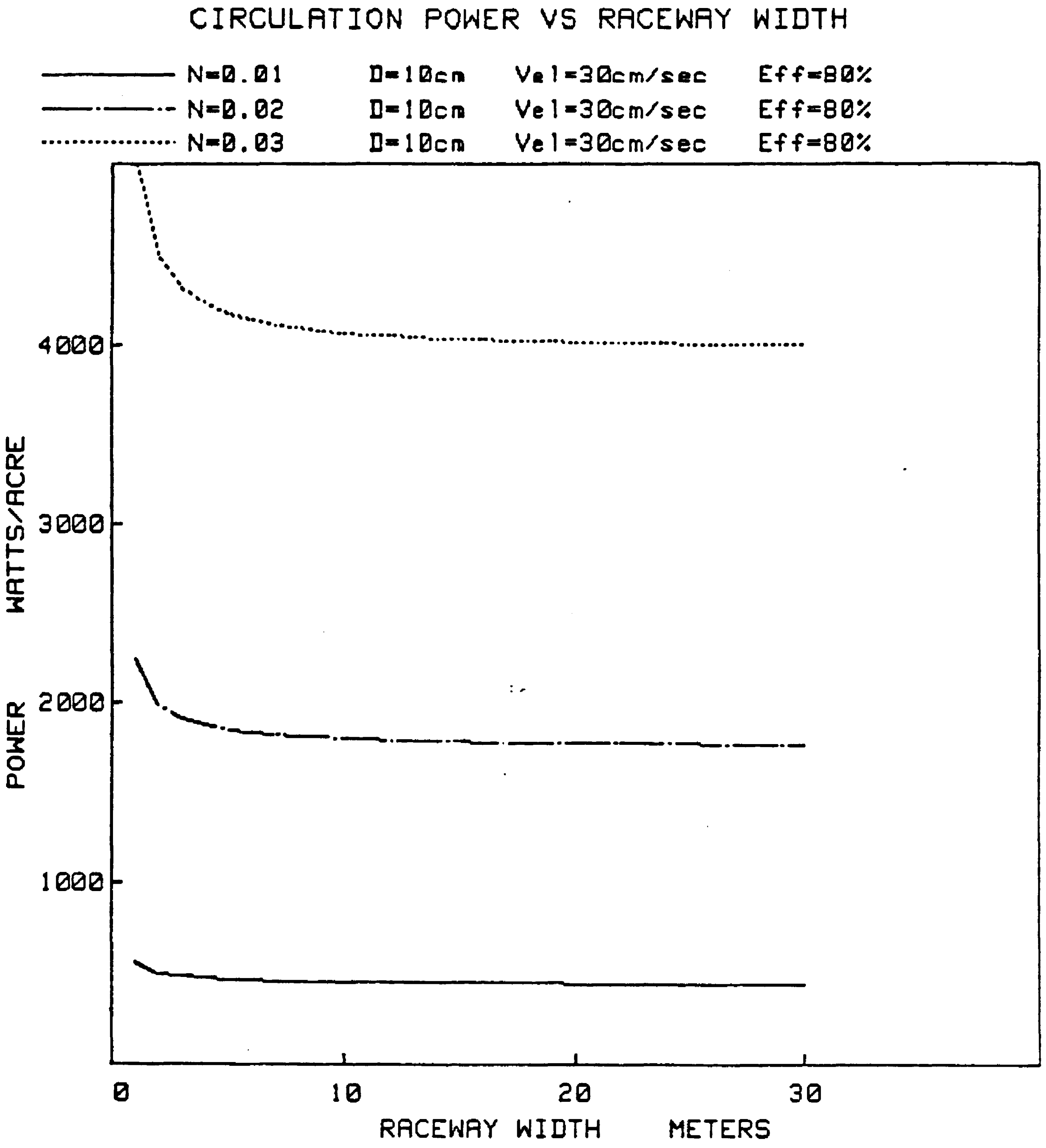

CIRCULATION POWER VS RACEWAY WIDTH
N=0.01 D=10cm Vel=30cm/sec Eff=80%
N=0.02 D=10cm Vel=30cm/sec Eff=80%
N=0.03 D=10cm Vel=30cm/sec Eff=80%
POWER WATTS/ACRE
4000
3000
2000
1000
0
10
20
30
RACEWAY WIDTH METERS

Figure 13

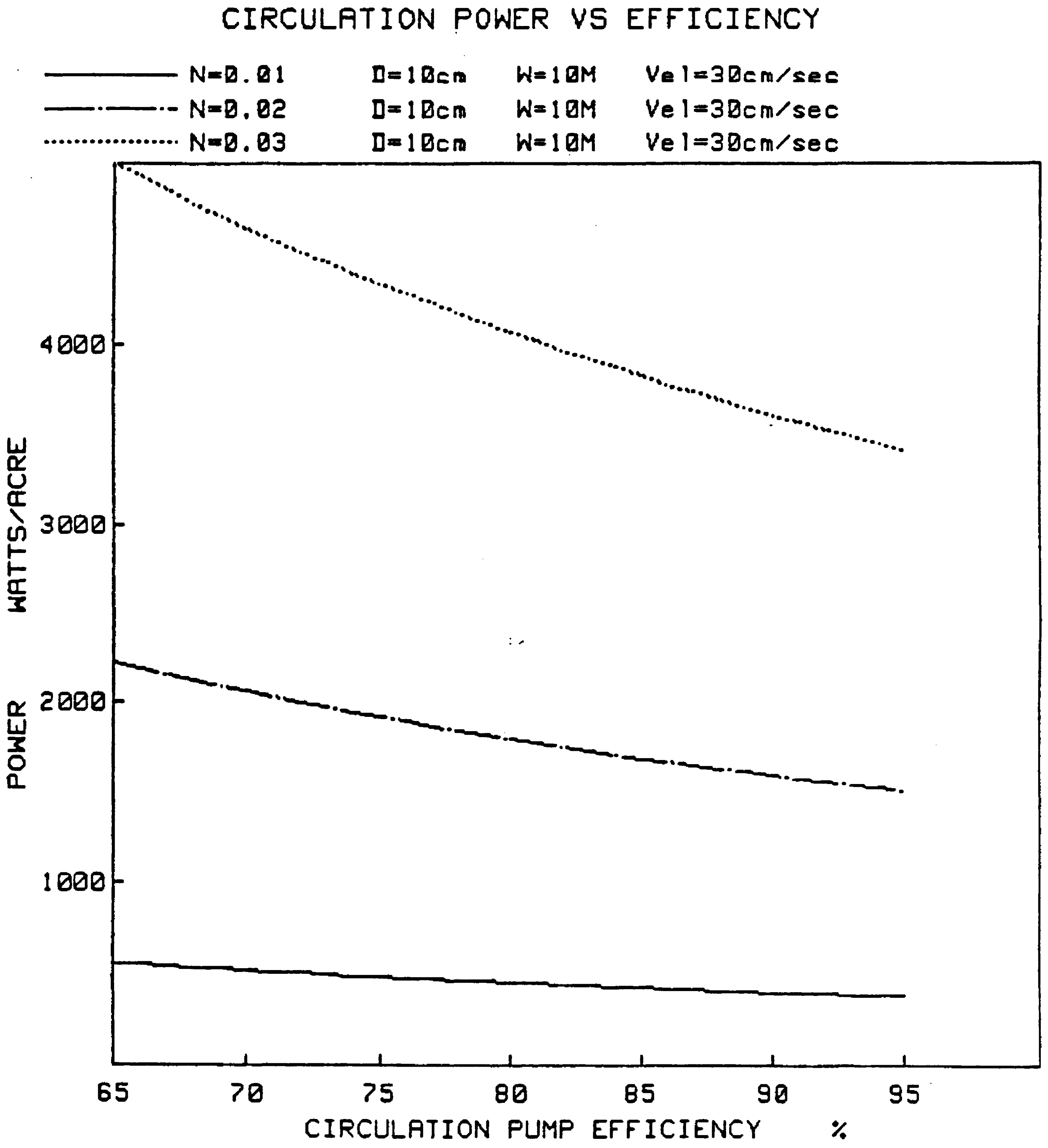

CIRCULATION POWER VS EFFICIENCY
N=0.01 D=10cm W=10M Vel=30cm/sec
N=0.02 D=10cm W=10M Vel=30cm/sec
N=0.03 D=10cm W=10M Vel=30cm/sec
POWER WATTS/ACRE
1000
2000
3000
4000
65
70
75
80
85
90
95
CIRCULATION PUMP EFFICIENCY %

Figure 14

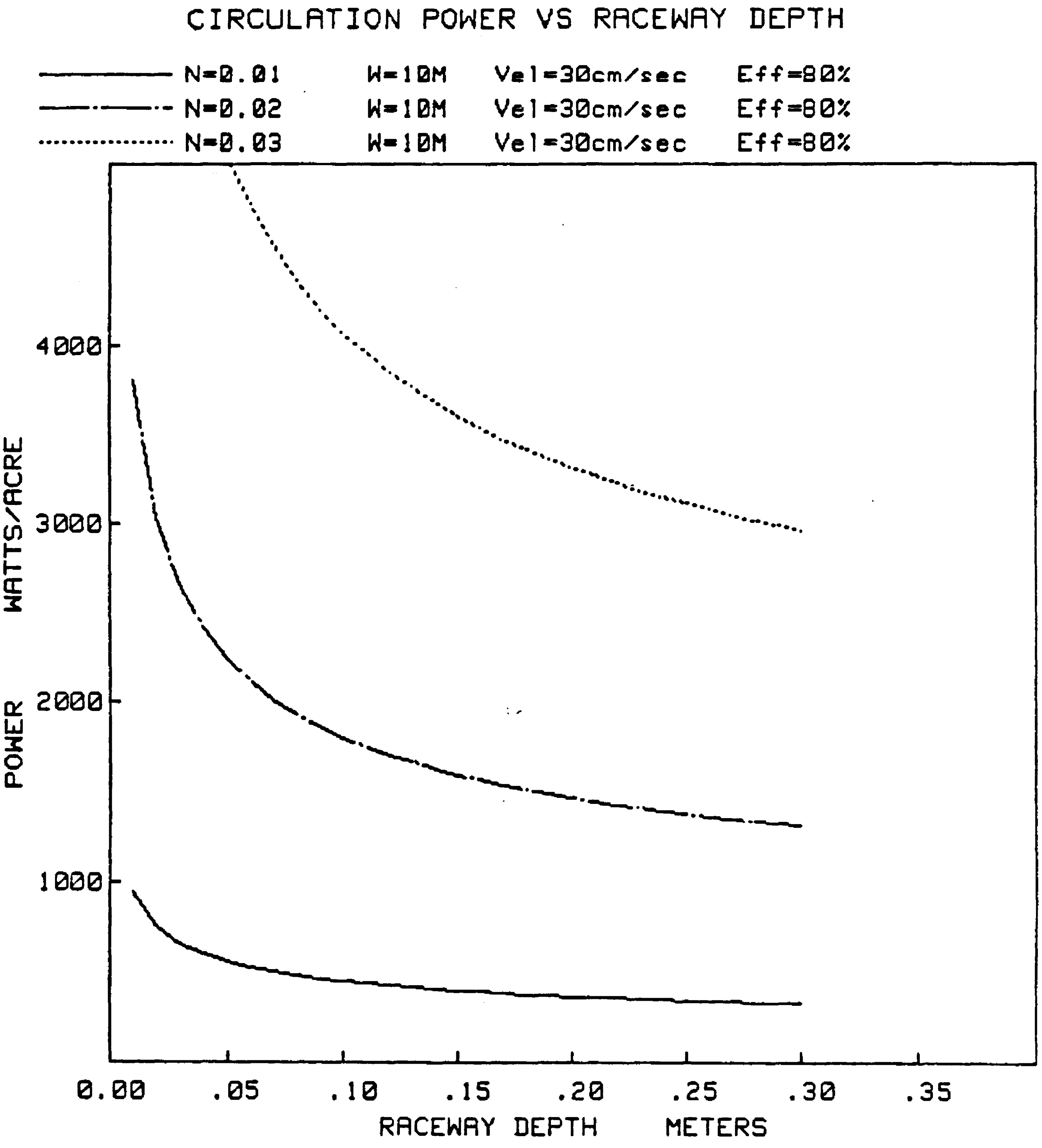

CIRCULATION POWER VS RACEWAY DEPTH
N=0.01 W=10M Vel=30cm/sec Eff=80%
N=0.02 W=10M Vel=30cm/sec Eff=80%
N=0.03 W=10M Vel=30cm/sec Eff=80%
POWER WATTS/ACRE
4000
3000
2000
1000
0.00
.05
.10
.15
.20
.25
.30
.35
RACEWAY DEPTH METERS

Figure 15

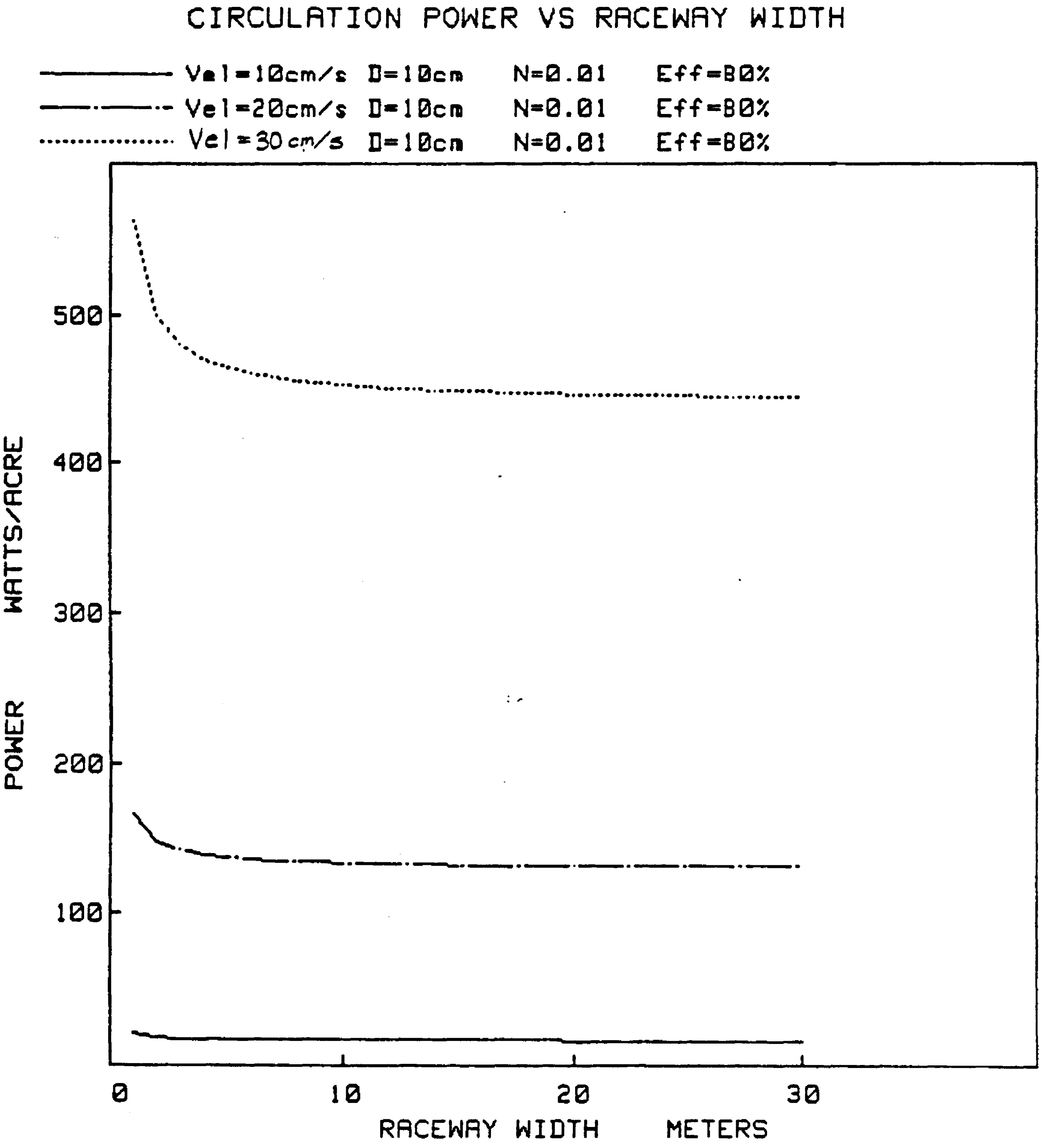

CIRCULATION POWER VS RACEWAY WIDTH
Vel=10cm/s D=10cm N=0.01 Eff=80%
Vel=20cm/s D=10cm N=0.01 Eff=80%
Vel=30cm/s D=10cm N=0.01 Eff=80%
POWER WATTS/ACRE
500
400
300
200
100
0
10
20
30
RACEWAY WIDTH METERS

Figure 16

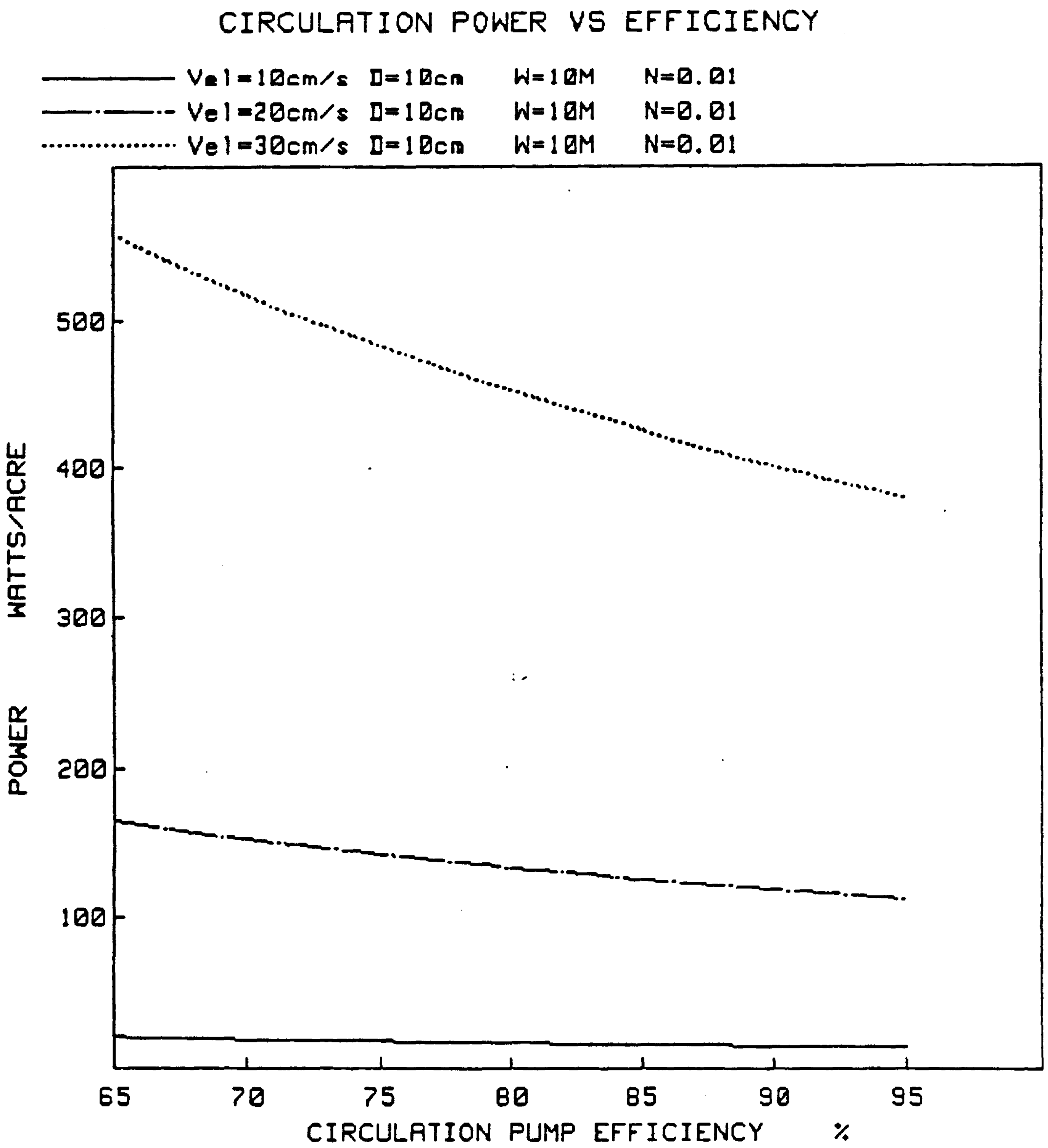
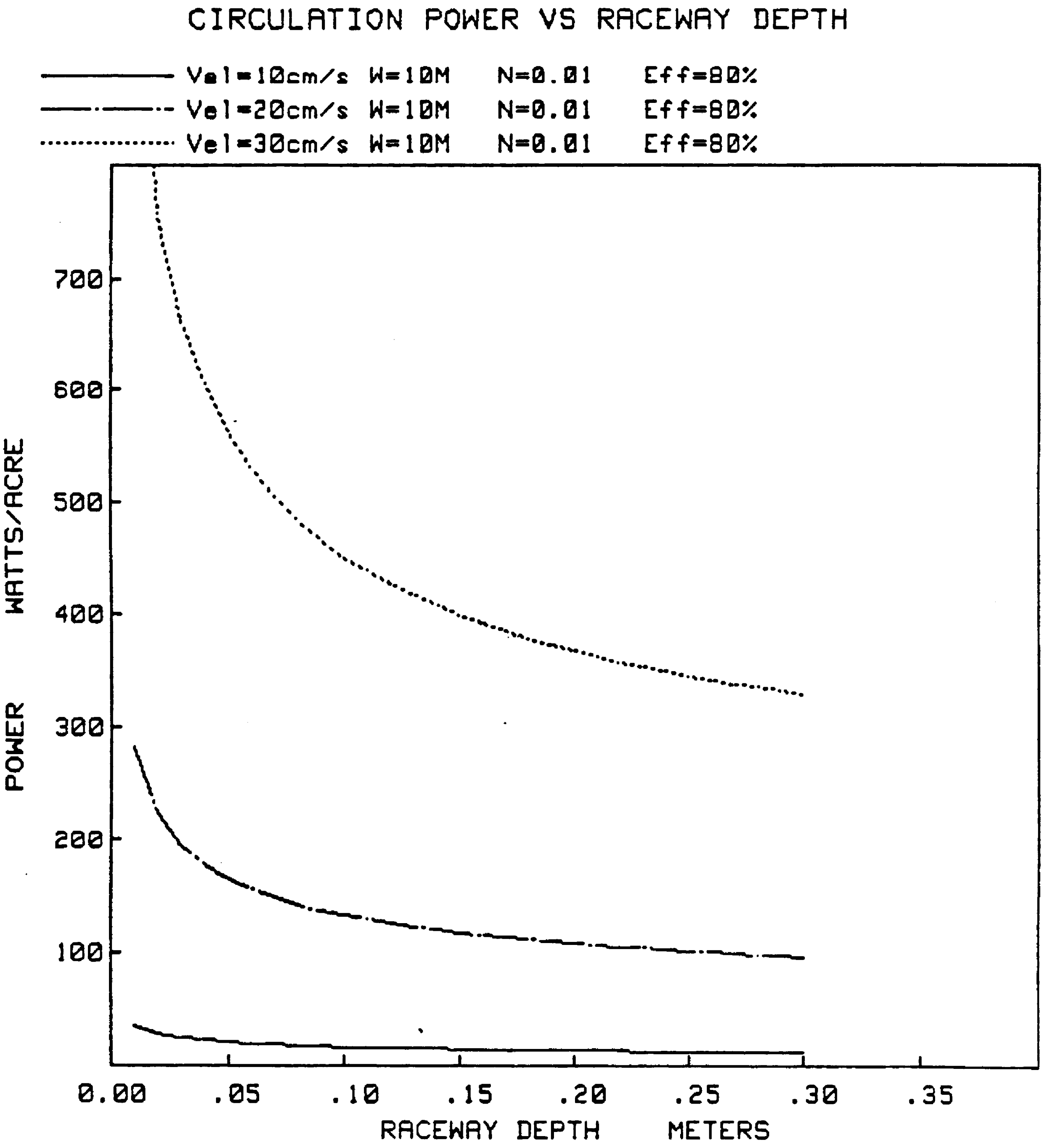

CIRCULATION POWER VS EFFICIENCY
Vel=10cm/s D=10cm W=10M N=0.01
Vel=20cm/s D=10cm W=10M N=0.01
Vel=30cm/s D=10cm W=10M N=0.01
POWER WATTS/ACRE
500
400
300
200
100
65
70
75
80
85
90
95
CIRCULATION PUMP EFFICIENCY %

Figure 17



CIRCULATION POWER VS RACEWAY DEPTH
Vel=10cm/s W=10M N=0.01 Eff=80%
Vel=20cm/s W=10M N=0.01 Eff=80%
Vel=30cm/s W=10M N=0.01 Eff=80%
POWER WATTS/ACRE
700
600
500
400
300
200
100
0.00
.05
.10
.15
.20
.25
.30
.35
RACEWAY DEPTH METERS

Figure 18

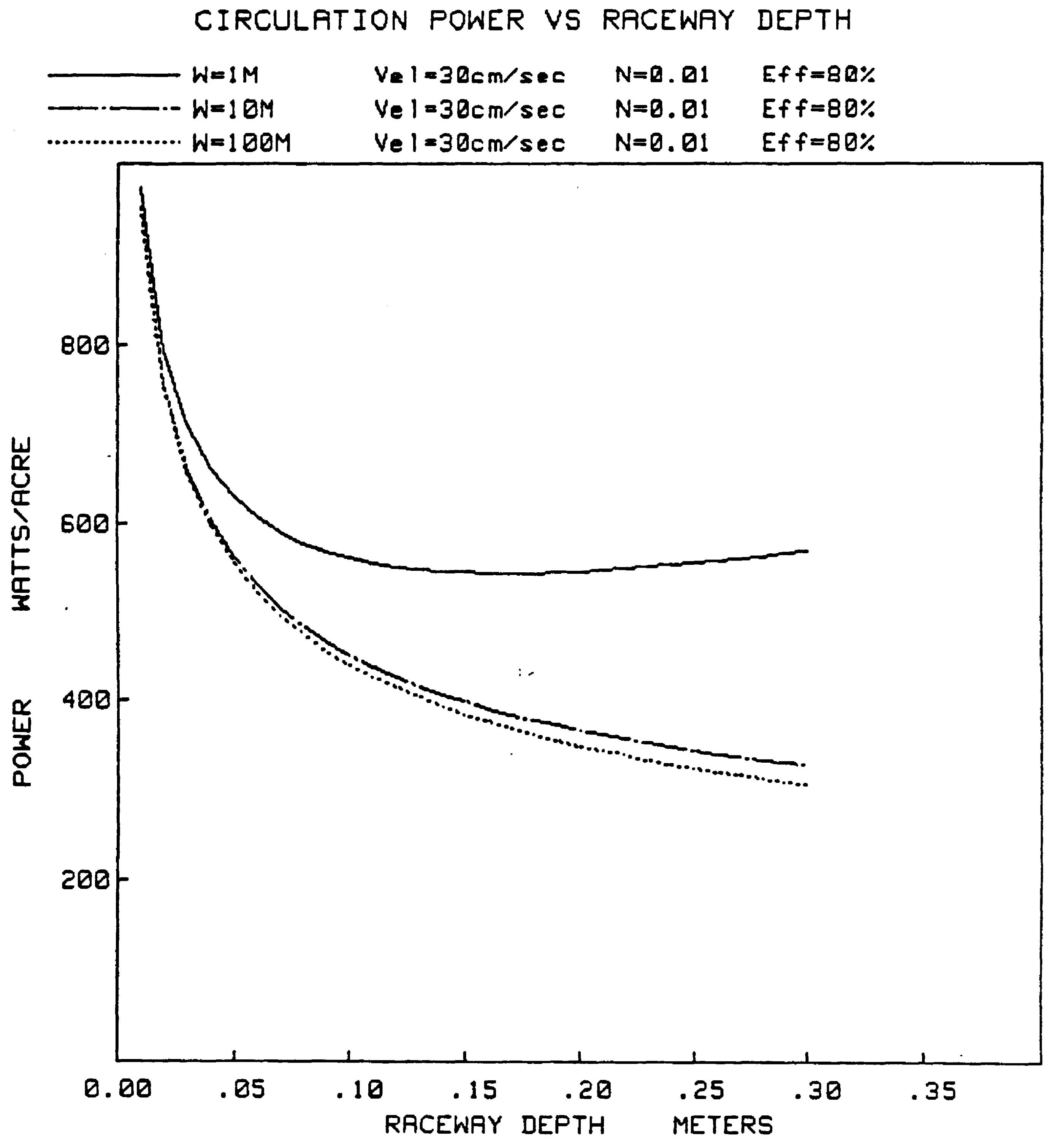

CIRCULATION POWER VS RACEWAY DEPTH
W=1M Vel=30cm/sec N=0.01 Eff=80%
W=10M Vel=30cm/sec N=0.01 Eff=80%
W=100M Vel=30cm/sec N=0.01 Eff=80%
800
600
400
200
POWER WATTS/ACRE
0.00
.05
.10
.15
.20
.25
.30
.35
RACEWAY DEPTH METERS

Figure 19

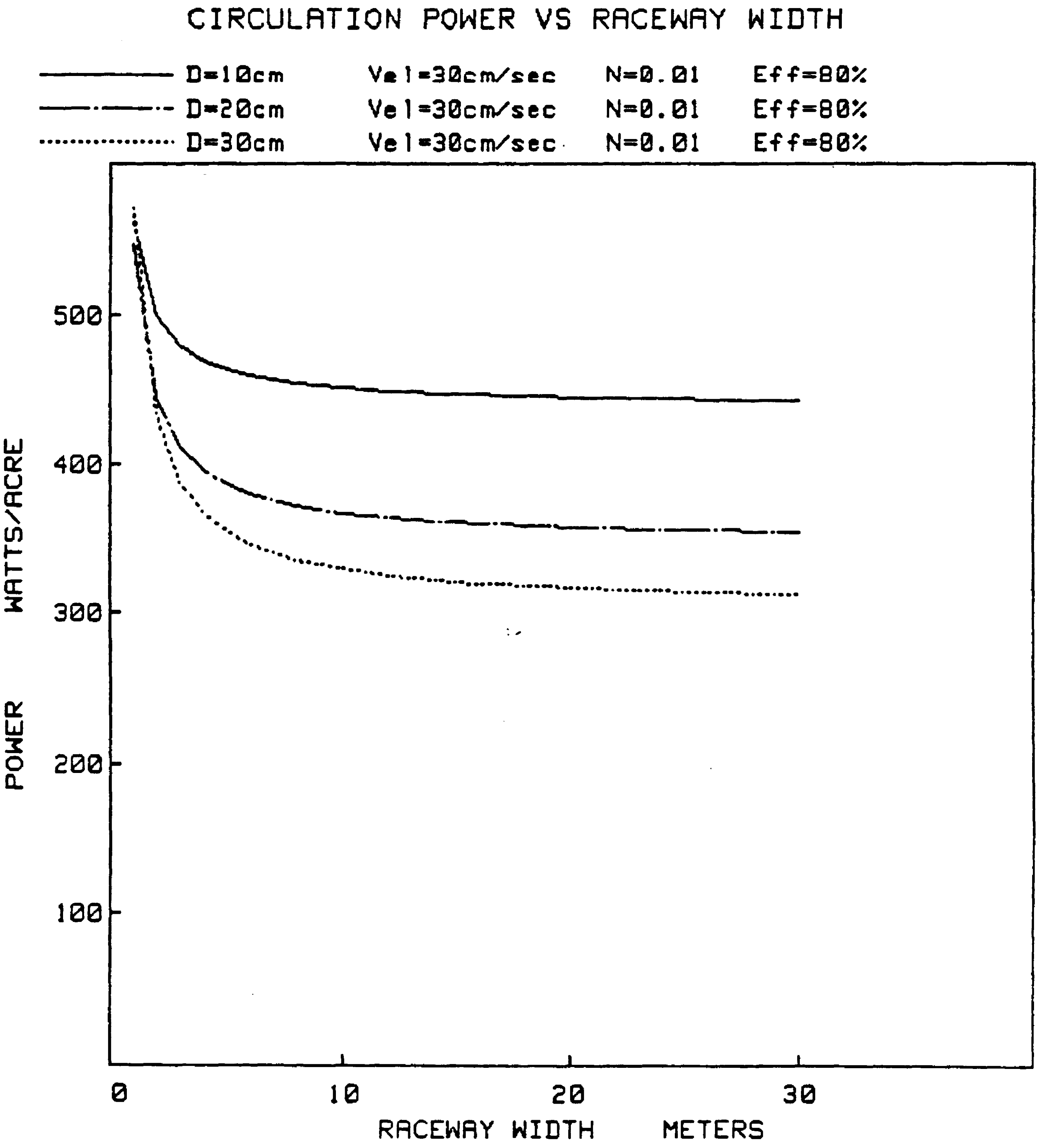

CIRCULATION POWER VS RACEWAY WIDTH
D=10cm Vel=30cm/sec N=0.01 Eff=80%
D=20cm Vel=30cm/sec N=0.01 Eff=80%
D=30cm Vel=30cm/sec N=0.01 Eff=80%
POWER WATTS/ACRE
500
400
300
200
100
0
10
20
30
RACEWAY WIDTH METERS

Figure 20

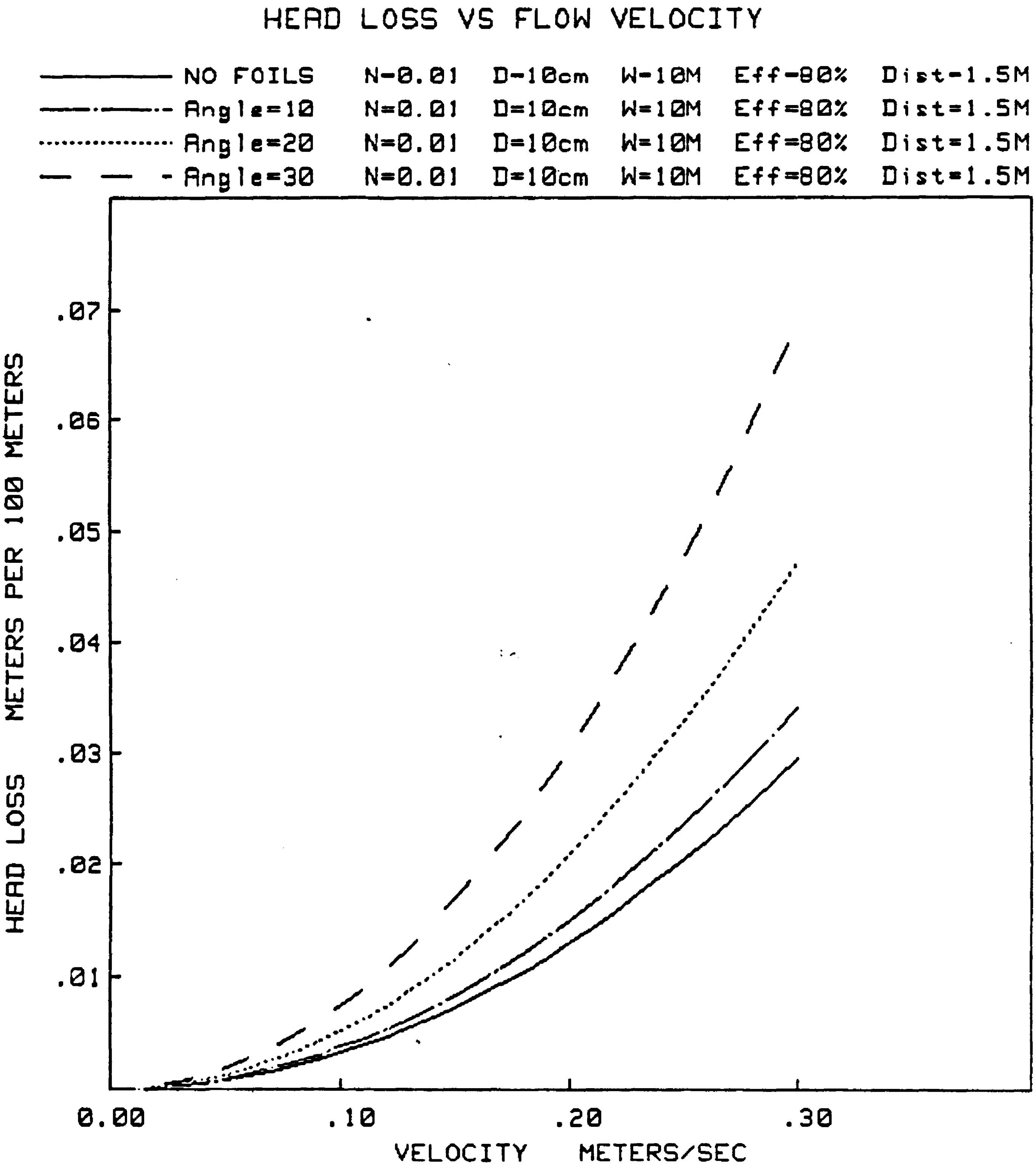

HEAD LOSS VS FLOW VELOCITY
NO FOILS N-0.01 D-10cm W-10M Eff-80% Dist-1.5M
Angle=10 N=0.01 D=10cm W=10M Eff=80% Dist=1.5M
Angle=20 N=0.01 D=10cm W=10M Eff=80% Dist=1.5M
Angle=30 N=0.01 D=10cm W=10M Eff=80% Dist=1.5M
HEAD LOSS METERS PER 100 METERS
.07
.06
.05
.04
.03
.02
.01
0.00
.10
.20
.30
VELOCITY METERS/SEC

Figure 21

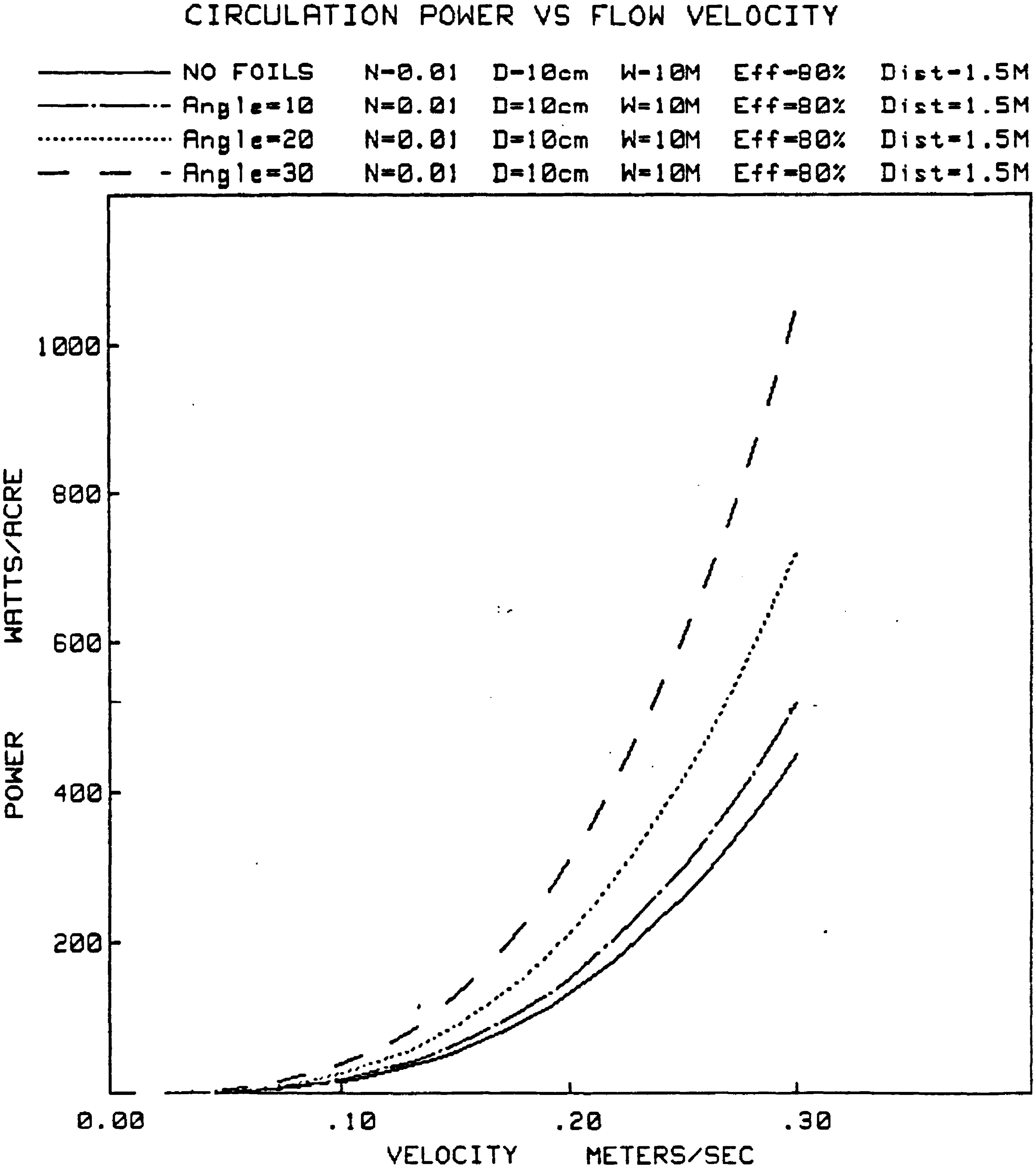

CIRCULATION POWER VS FLOW VELOCITY
NO FOILS N=0.01 D=10cm W=10M Eff=80% Dist=1.5M
Angle=10 N=0.01 D=10cm W=10M Eff=80% Dist=1.5M
Angle=20 N=0.01 D=10cm W=10M Eff=80% Dist=1.5M
Angle=30 N=0.01 D=10cm W=10M Eff=80% Dist=1.5M
1000
800
600
400
200
POWER WATTS/ACRE
0.00
.10
.20
.30
VELOCITY METERS/SEC

Figure 22

CONCLUSIONS

The object of this study was to determine which parameters were most important to power consumption and head loss in long shallow raceway systems. The understanding of which parameters are most significant allows us to envision where power consumption or head losses can be most easily reduced. Based on the curves alone, without taking into account practical considerations, the following rankings can be made:

1. Velocity is the most important parameter. A 10% decrease in velocity will reduce power consumption by 27% and head loss by 19%.

Why look at 30s Ken?

2. Friction factor is the next most important parameter. A 10% decrease in friction factor will decrease power consumption and head loss 19%.

3. Foil angle changes will affect both power consumption and head loss. The decrease in power consumption due to a 10% decrease in foil angle is dependent upon the flow velocity, the distance between foil sections and position along the power versus foil angle curve. At Laws' flow velocity of 30 cm/sec and at 1.5m distance between foil sections, the following power reductions are possible with a 10% decrease in foil angle.

10% Foil Angle Reduction	Corresponding Power Reduction
30° - 27°	16.9%
20° - 18°	10.3%
10° - 9°	1.4%

4. Increasing the distance between foil sections is important to both power consumption and head loss reduction. The decrease in power consumption due to a 10% increase in foil section spacing is dependent on flow velocity, foil angle spacing and position along the power vs foil section spacing curve. For 30 cm/sec flow velocity and at a 20° foil angle the following power reductions are possible for a 10% increase in foil section spacing:

10% Foil Section Spacing Increases	Corresponding Power Reduction
1.5 - 1.65 m	3.5%
5.0 - 5.5 m	1.3%
10.0 - 11 m	0.8%

5. Increasing the circulation pump efficiency by 10%, i.e. from 60% to 65% efficiency, will result in a power reduction of 9.1%. Pump efficiency improvements have no effect on head loss.

6. If raceway width is much greater than raceway depth, any increase in depth will result in a decrease in power consumption and a head loss. This effect is also subject to diminishing returns. The following table illustrates the effect of 10% depth increases at various depth levels.

so why stay so shallow

10% Depth Increases	Power Reduction
5 - 5.5 cm	3.0%
10 - 11.0 cm	2.9%
15 - 16.5 cm	2.8%

This contradicts circulation speed suggest deeper, slower ponds unless productivity tradeoff can be established

7. Width is important only in the sense that it must be kept greater than a given minimum. If the width is at least 30 times greater than its raceway depth, the effect of width on power consumption is minimal.

If practical considerations and the necessity to adhere to the Laws' basic raceway system are included in this analysis, a number of recommendations can be made.

With respect to velocity reduction, we are faced with the necessity of maintaining a 30 cm/sec flow velocity in order to achieve Laws' production. However, the algae is only growing and multiplying during the day. At night the flow velocity could be reduced. An obvious questions which requires further study by Ed Laws is how much can the flow velocity be reduced at night? A question which requires further engineering analysis is what is the best pond configuration to allow a velocity reduction at night? Two configurations immediately come to mind: A flat raceway with a paddle wheel or pump pushing the water around the system; alternatively, a sloped raceway which moves water at a night time velocity with only the assistance of a small lift pump, but is equipped with paddle wheels to increase the flow velocity during the daylight hours. A decision on which configuration is best must consider ease of construction, power failure contingencies, and a pump versus paddle wheel comparison study. MOE will further study these subjects prior to a final recommendation.

? Are we?

Two questions come to mind relative to reducing friction factor in the raceway surfaces. First, how much of a difference is there between roughness values for different liner materials? Second, will the accuracy of grading and leveling the surface area under the liner material be more important than the roughness of the material itself to the overall roughness coefficient? From research that MOE has already conducted it is apparent that there is little information about friction factors or roughness coefficients for various liner materials. In addition, the installation of flexible liner materials, which are often installed with a certain percentage of slack that causes folds to occur, will have as much influence on friction factor as the surface roughness coefficient itself. Further thought must be given to how surface roughness before and after installation of a flexible liner can be incorporated in an overall cost comparison with a more traditional materials such as concrete.

In order to verify the head loss and power consumption values attributed to the addition of mixing foils in this study, a series of hydraulic studies should be conducted by HNEI. The overall objective of these studies should be the determination of a drag/turbulence ratio for different mixing foils, and if possible, correlate these results with production rates in Laws' ponds. Phases which should be included in this study would include the determination of:

1. Head loss per unit length for Laws' current mixing foil arrays.
2. The effect of foil angle.
3. The effect of foil size, length and width, especially as related to water depth.
4. The effect of various foil shapes, i.e. air foils, curved plates.
5. The effect of foil spacing.

Circulation pump efficiency is controlled by the pump or paddle wheel design and the associated prime mover. Generally, large low head pumps have very good efficiency, but are extremely expensive. A paddle wheel is probably not as efficient as a low head pump. However, a paddle wheel's initial cost will be much lower and the possibility of linking several paddle wheels together to be driven by one prime mover is more plausible. A tradeoff analysis should be conducted which would include consideration of a the initial cost, service life and the operating costs of a pump and paddle wheel.

There are several practical considerations that accompany an increase in raceway water depth. These considerations may be more important to the overall system than the potential savings in power due to an increase in depth. Considerations that support an increase in water depth include:

1. Greater water depth would help to secure pond liner against any undesirable shrinkage or shifting.
2. Greater water depth would cover grading inaccuracies, heaving, etc.
3. Greater water depth would aid CO_2 absorption.
4. Greater water depth would mean lower head losses and so fewer paddlewheels per unit length of raceway.

Considerations that may have a negative impact on water depth include:

1. What is the greatest depth at which Laws' production rates/densities can be attained?
2. Greater depth means more water to supply and dispose of.
3. Greater depth may mean wider foils to attain the required turbulence, what effect will this have on head loss?

Obviously, further study of these considerations is required before we can conclude that an increase in water depth to achieve lower circulation power is desirable.

It will be practical and easy to achieve a raceway width that is 30 times greater than the raceway depth. A more important question is just how wide a raceway can be tolerated. The answer to this question seems to involve numerous practical considerations. Among them:

1. Structural design of the paddle wheel
2. Design of the power transmission system for the paddle wheels
3. Pump diffuser size limitation.
4. Flow uniformity with respect to width.
5. Cleaning of a wide raceway.
6. Convenience of construction i.e. size of grader blade, size of liner sheets, size of concrete laying machine.
7. Effects on harvesting

Further information should be gathered to set a practical limit on the width of a raceway.

When power per unit area is being plotted, raceway length is not an important consideration. However, there are several practical considerations that will influence raceway length. The distance between paddle wheels or pump units to raise the head of the flowing water will be determined by the variation in depth we can tolerate. The water will be raised by a pump or paddle wheel up to a given head and then will flow down the raceway with steadily decreasing depth until it reaches the next paddle wheel. The minimum and maximum depth that can be tolerated and still achieve Laws' production rate will determine how far apart these paddle wheels are placed. The CO_2 depletion rate from the water will influence the overall length of the raceway. It would be most convenient to only bubble CO_2 into the system at one point in the raceway so that the CO_2 distribution network can be minimized. To accomplish this the CO_2 depletion rate from the water and the CO_2 depletion tolerance of the algae must correspond so that in one complete circuit around the raceway the CO_2 content in the water is not reduced below the algae's CO_2 depletion tolerance. The length of the raceway is very important to this

CO_2 supply/consumption system. Further study by Ed Laws to determine the algae's CO_2 depletion tolerance and to determine the CO_2 content in the water both immediately before and immediately after CO_2 is added in his current system would be most valuable. This information could probably be obtained by translating the current values for pH before and after CO_2 addition into CO_2 saturation levels.

SUMMARY OF RECOMMENDATIONS

Among the recommendations made throughout this report are numerous studies and experiments to be undertaken by MOE and other team members. It is recognized that only limited time and money can realistically be spent in preparing the conceptual design and experimental facility design under this SERI procurement. We cannot obtain all the answers by the end of this project. However, such studies and experimentation should be recorded for potential use in the experimental program that is to follow. Therefore, the listing provided below summarizes the recommendations made by MOE and others to date:

1. Flow velocity reductions at night. (Laws)
2. Study of sloped vs. flat raceways, including cost, convenience and effects on other mechanical systems within raceways. (MOE)
3. Study to find limitations on raceway width. (MOE)
4. Comparison of circulation pumps and paddle wheels including effects of loss of aeration from Laws' current airlift system. (MOE, Laws)
5. Study to determine feasibility/potential gains from increasing water depth and/or algae depth tolerance. (MOE, HNEI, LAWS)
6. Comparison of pond liners. (MOE)
7. Study of CO_2 depletion rate of algae as a function of length and corresponding CO_2 saturation levels in the water before and after CO_2 addition. (LAWS)
8. Hydraulic studies including: (HNEI)

    a. Head loss per unit length for Laws' current mixing foil arrays.
    b. The effect of foil angle.
    c. The effect of foil size, length and width, especially as related to water depth.
    d. The effect of various foil shapes, i.e. air foils, curved plates.
    e. The effect of foil spacing.

Note: Parenthesis indicate team members that would be involved in each study.

APPENDICES

1. Microalgae Pond Calculations
2. Pond Hydrodynamic Calculations
3. Head Loss Plots

EQNs TO DEVELOP COMPUTER PROG. FOR
MicroAlgae Facility

CHEZY EQN: $v = C\sqrt{RS}$

where $R = \dfrac{\text{Flow Area } (A)}{\text{WETTED PER. } (P)}$

$S = \dfrac{\text{head loss } (h_f)}{\text{Length } (L)}$

C = CHEZY COEFF.

v = Flow vel.

CHEZY EQN Appropriate for open channel, uniform flow. Can also be used for non-uniform flow where Δdepth over channel length is small.

CHEZY EQN REARRANGED

$$h_f = \frac{Lv^2}{C^2 R}$$

To find C: MANNING EQN IS ACCEPTED for large & small dia. pipes & channels.

$$C = \frac{0.82\, R^{\frac{1}{6}}}{n}$$ where n = characteristic of surface roughness

FOR RECTANGULAR CHANNEL CROSS SECTION

Since $R = \frac{\text{depth}(d) \cdot \text{width}(w)}{\text{width}(w) + 2 * \text{depth}(d)}$

$$\therefore \quad C = 0.82 \left(\frac{dw}{w+2d}\right)^{\frac{1}{6}} \Big/ n$$

AND

$$h_f = 1.49 \frac{L \quad v^2 \; n^2}{\left(\frac{dw}{w+2d}\right)^{1/3} \left(\frac{dw}{w+2d}\right)} = \frac{1.49 L v^2 n^2}{\left(\frac{dw}{w+2d}\right)^{4/3}}$$

If $w \gg d$ ie. $w = 10\text{ m}$ $d = 10\text{ cm}$

$d = 1\%$ of width.

$$\frac{dw}{w+2d} \cong \frac{d\cancel{w}}{\cancel{w}} = d$$

AND

$$h_f = 1.49 \frac{L v^2 n^2}{d^{4/3}}$$

$PWR = Q \rho g h_f$ $\qquad Q = v \cdot d \cdot w$

with $w \gg d$

$$PWR = v \cdot d \cdot w \cdot \rho \cdot g \left(\frac{1.49 L v^2 n^2}{{}^{4/3}}\right)$$

$$\boxed{\frac{P_{WR}}{LW} = 1.49 \rho g \frac{v^3 n^2}{d^{1/3}}}$$

conclusion for $W \gg d$

Pwr drops as d increases.

If $W \not\gg d$

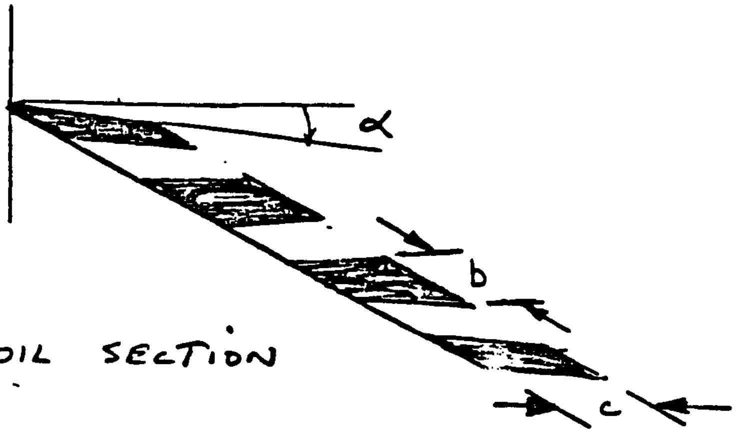
$$P_{WR} = \overbrace{v\,d\,W}^{Q}\,\rho\cdot g\left(\frac{1.49\,L\,v^2 n^2}{\left(\frac{dW}{W+2d}\right)^{4/3}}\right)$$

$$\frac{P_{WR}}{LW} = 1.49\,\rho g v^3 n^2 d\left(\frac{W+2d}{dW}\right)^{4/3}$$

$$\boxed{\frac{P_{WR}}{LW} = \frac{1.49\,\rho g v^3 n^2}{d^{\frac{1}{3}}}\left(1+2\,d/W\right)^{4/3}}$$

USE THIS MORE GENERAL FORM IN PROGRAM.

PROJECT: Pond Hydrodynamics
DATE:
BY:



AIR FOIL SECTION

TOTAL DRAG DUE TO ONE AIR FOIL SECTION

$$D_{TOTAL} = D_{PRESSURE} + D_{INDUCED} + D_{SKIN\ FRICTION}$$

FOR FLAT PLATE NOT ALIGNED WITH FLOW, $D_{pressure}$ will be most significant TERM.

$$D_{TOTAL} \cong D_{pressure}.\ (D_p)$$

$$D_p = C_D A_{proj} \rho \frac{V^2}{2}$$

C_D = Drag coeff, function of α, SEE ATTACHMENTS

$A_{proj} = B \cdot C \cdot \sin \alpha$

where $B = \sum b$ ACROSS CHANNEL width.

ρ = FLUID DENSITY (1025 Kg/m³ for SEAWATER)

V = FLUID VELOCITY

HEAD LOSS DUE TO AIRFOIL Drag

$$\text{Pressure Loss} = \frac{\text{Drag}}{\text{Pond Depth } (d) \times \text{width } (W)}$$

$$\text{Head loss} = \frac{\text{Pressure loss}}{\rho \cdot g}$$

$$\text{Head loss} = \frac{C_D A_{proj} \rho \frac{V^2}{2}}{d \cdot W \cdot \rho \cdot g}$$

To generalize A_{proj} for different width ponds,

LET $A_{proj} = \left(\frac{A_{proj}}{W}\right)_{LAWS} \cdot W$

$$\text{Head loss} = \frac{C_D \left(\frac{A_{proj}}{W}\right)_{LAWS} \cdot W \cdot \rho \frac{V^2}{2}}{d \cdot W \rho g}$$

Above eqn is for one airfoil section, to generalize this eqn multiply by

$\frac{L}{dist\_btn}$ where L = Total Pond Length
dist.btn = distance between Foil sections

$$\text{Head loss} = \frac{C_D \left(\frac{A_{proj}}{W}\right)_{LAWS} \cdot W \cdot \rho \frac{V^2}{2} \cdot L}{d \cdot W \cdot \rho \cdot g \cdot dist\_btn}$$

For LAWS' current Ponds

depth specific
$$\begin{cases} b = 4.25'' \\ c = 4.25'' \\ \alpha \cong 20^\circ \ ? \end{cases} \qquad B = 3 \times 4.25 = 12.75''$$

$$A_{proj} = 18.5 \text{ in}^2 \quad (0.01196 \text{ m}^2)$$

$$V = 0.30 \ \frac{\text{m}}{\text{sec}} \qquad W = 2' \ (0.6098 \text{ m})$$

dist. btn = 5' (1.524 m)

FINAL FORM OF HEAD LOSS EQN PER UNIT LENGTH

$$\frac{\text{HEAD LOSS}}{L} = \frac{C_D \left(\frac{A_{proj}}{W}\right)_{LAWS} \cdot \frac{V^2}{2}}{d \cdot g \cdot \text{dist. btn.}}$$

FOR LAWS' CURRENT RACEWAYS, HOW MUCH HEAD LOSS IS ADDED BY THIS DRAG TERM.

$$\frac{\text{HD LOSS}}{L} = \frac{C_D (0.01962)}{0.10 \cdot (1.524)} \left[\frac{V^2}{2g}\right]$$

$$= C_D (0.1287) \frac{V^2}{2g}.$$

FROM HOERNER (ATTACHED)

$C_D = C_N \sin\alpha$

AT $\alpha = 20^\circ$ $C_N = 0.86$

$C_N \cong (1.75/40.22)\,\alpha$

$C_D = 0.29$

$$\frac{\text{HEAD LOSS}}{\text{Length}} = 0.038 \left(\frac{V^2}{2g}\right)$$

THIS CAN BE COMPARED TO THE HEAD LOSS DUE TO FRICTION IN A SIMILAR CHANNEL

CHEZY EQN.

$$\left(\frac{\text{HEAD LOSS}}{L}\right)_{\text{FRICTION}} = \frac{V^2}{C^2 R}$$

$C =$ CHEZY COEFF $= \frac{0.82 R^{\frac{1}{6}}}{N}$

$R =$ Hyd. Radius $= \frac{W \cdot d}{W + 2d}$

$N =$ MANNINGS Roughness FACTOR

IN TERMS OF DYNAMIC HEAD.

$$\left(\frac{\text{HEAD LOSS}}{L}\right)_{\text{FRICTION}} = \frac{2g}{C^2 R}\left(\frac{V^2}{2g}\right)$$

$W = 10\text{m}$ $D = 0.10\text{ m}$ $N = 0.01\text{ m}^{\frac{1}{6}}$

$R = 0.098\text{ m}$ $C = 55.7$

$$\left(\frac{\text{HEAD LOSS}}{L}\right)_{\text{FRICTION}} = 0.065\left(\frac{V^2}{2g}\right)$$

$$\left(\frac{\text{HEAD LOSS}}{L}\right)_{\text{DRAG}} = 0.038\left(\frac{V^2}{2g}\right)$$

"FLUID DYNAMIC DRAG"
BY HOERNER

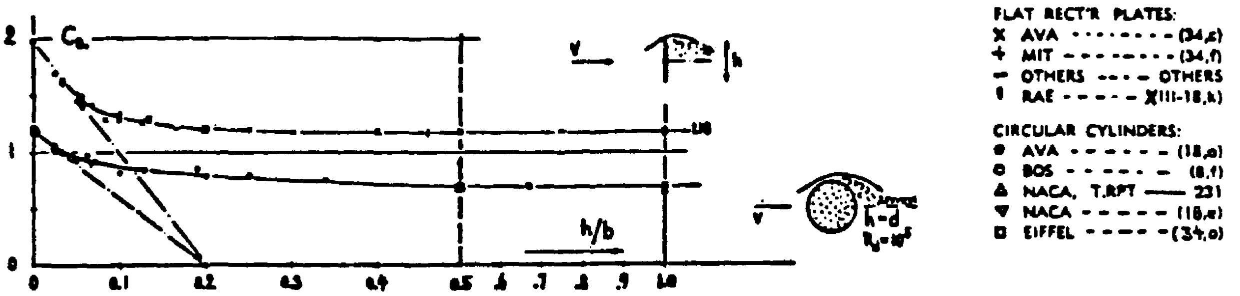


Figure 28. Drag coefficients of rectangular plates and circular cylinders as a function of their height (or diameter) to span ratio.

where $C_{Do\bullet}$ = coefficient in two-dimensional flow and "k" a constant in the order of 5.

Rear-Side Pressure. Plates in fluid flow normal to their surface, have highly negative pressures on their rear side. Because of wind-tunnel blocking, some discrepancies are found, however, with respect to the magnitude of the pressure coefficient as reported in various references (37). As likely values are suggested:

in 2 dimensions $C_{D\bullet} = 1.98$; $C_{prear} = -1.13$;
in 3 dimensions $C_{D\bullet} = 1.17$; $C_{prear} = -0.42$;

Plates At An Angle. Upon tilting three-dimensional plates to an angle against the direction of flow, away from $\alpha = 90°$, the normal-force coefficient as plotted in figure 29,a — remains approximately constant between $\Delta\alpha$ = plus and minus ≈ 45°. This observation seems to be the basis of an old theory of ship sailing. With $C_{normal} \approx 1.17 \approx$ constant, the lateral component of the sail is $C_L = 1.17 \cos\alpha$, while the drag component is $C_D = 1.17 \sin\alpha$. This analysis can only be correct, of course, in the range of wind-against-sail angles above $\alpha = 45°$ — as they were used in the old-time fully-rigged ships designed for sailing more or less in front of the trade winds.

Disk With Hole. As illustrated in figure 30, the drag of a disk (in pounds) is not reduced at first, upon cutting a hole in its center. Beyond $d_i/d_o = 0.25$, the drag decreases, however, more or less steadily. Based upon the area of the resulting ring, the drag coefficient increases and reaches a limiting value which is identical to that of the rectangular plate with $b/h = \infty$, that is $C_{D\bullet} = 1.98$. In the wake behind the ring, an annular vortex street must be expected similar to that as observed within the wake of a cylindrical ring (17). Between $d_i/d_o = 0.6$ and 0.8, evidently some change takes place in the flow pattern. Likely, the organization of the vortex system switches here from the three-dimensional to the two-dimensional type.

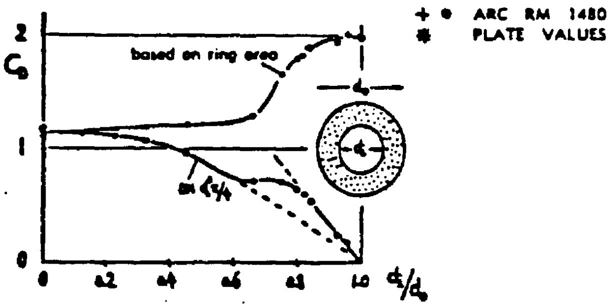
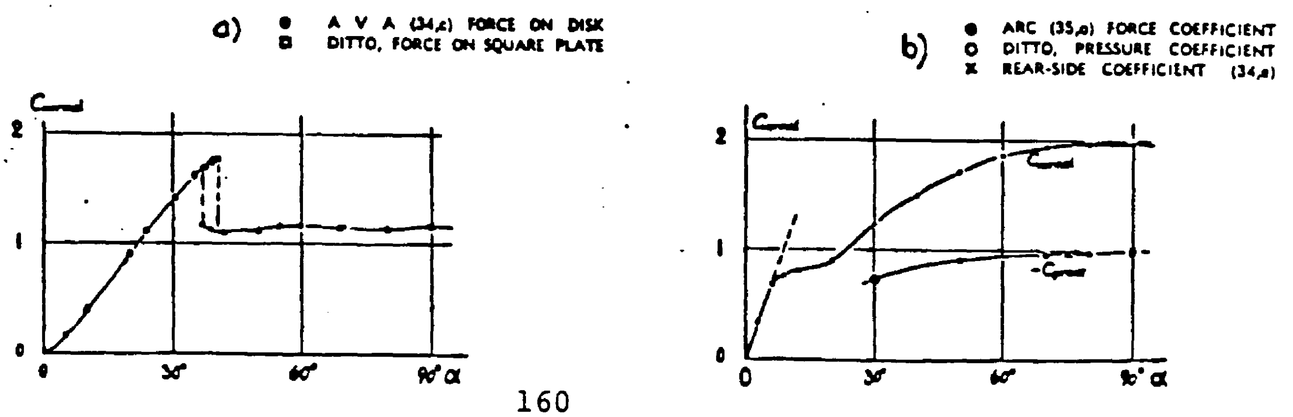


Figure 30. Drag coefficient of annular plates (rings), as reported in (34,d), at $R_{do} = 10^5$.

Figure 29. Normal-force coefficients of plates having square or circular shape (left), and in two-dimensional condition (right, between tunnel walls).



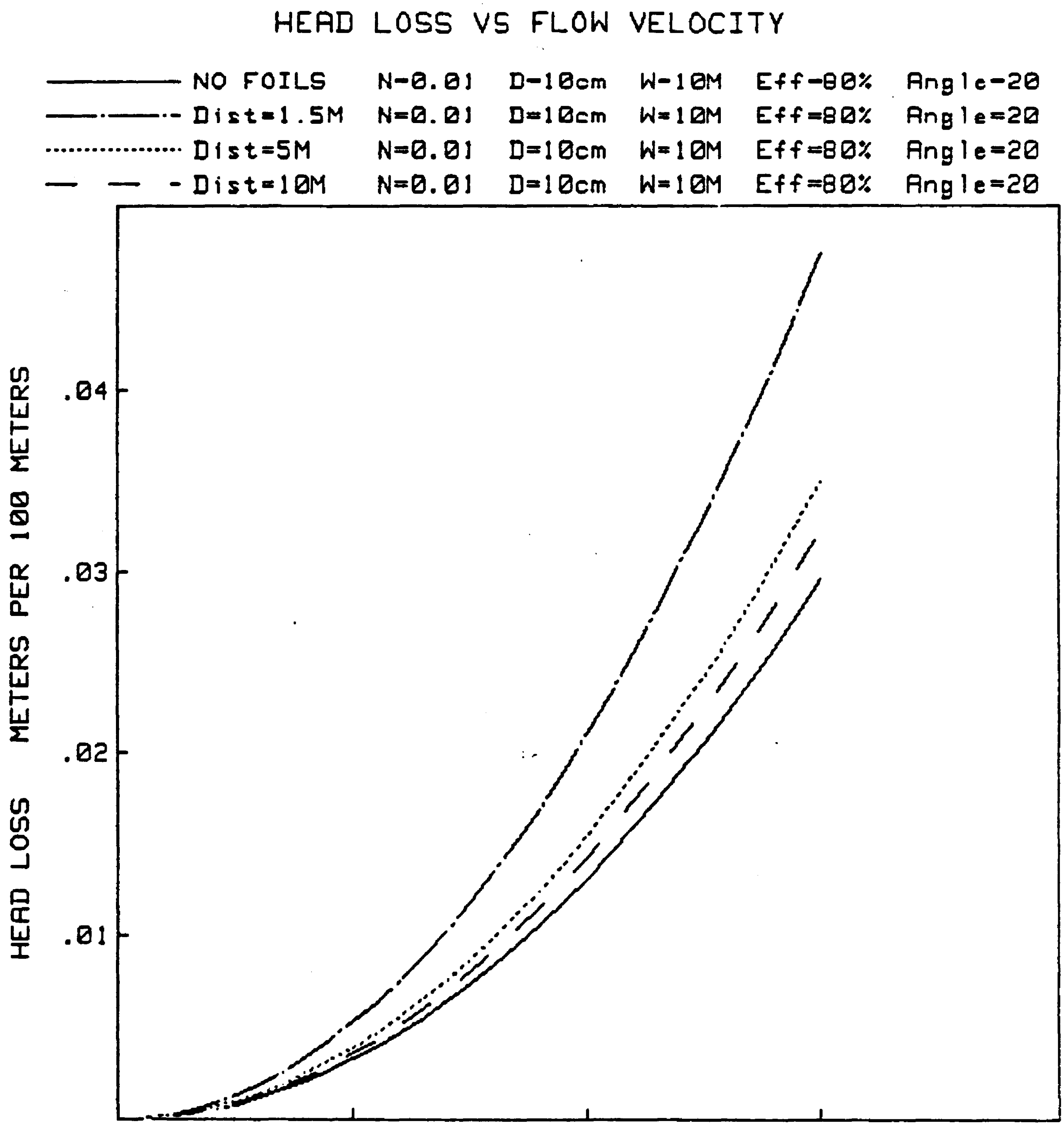

HEAD LOSS VS FLOW VELOCITY
NO FOILS N=0.01 D=10cm W=10M Eff=80% Angle=20
Dist=1.5M N=0.01 D=10cm W=10M Eff=80% Angle=20
Dist=5M N=0.01 D=10cm W=10M Eff=80% Angle=20
Dist=10M N=0.01 D=10cm W=10M Eff=80% Angle=20
.04
.03
.02
.01
HEAD LOSS METERS PER 100 METERS
0.00
.10
.20
.30
VELOCITY METERS/SEC

Figure A-1

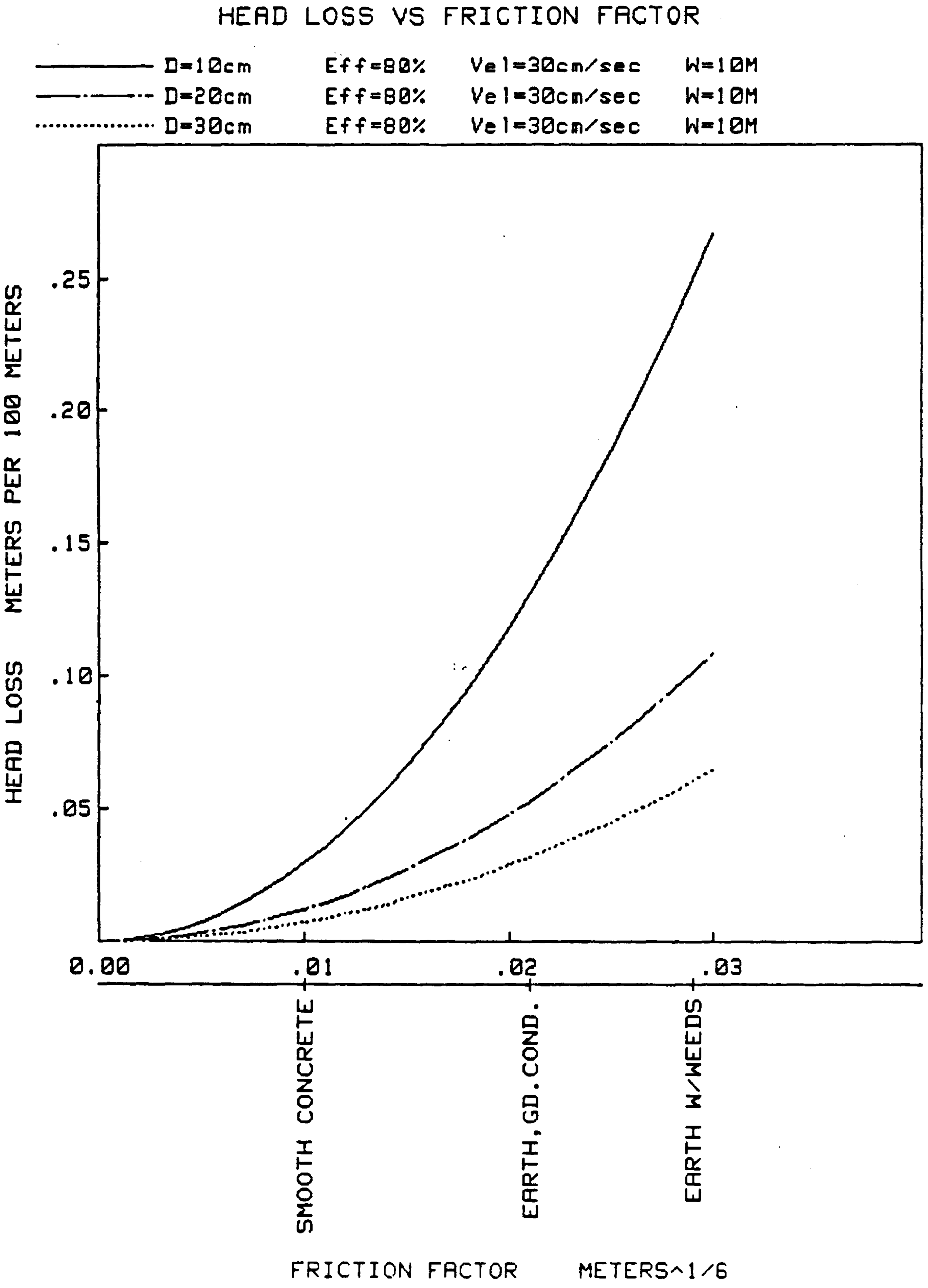

HEAD LOSS VS FRICTION FACTOR
D=10cm Eff=80% Vel=30cm/sec W=10M
D=20cm Eff=80% Vel=30cm/sec W=10M
D=30cm Eff=80% Vel=30cm/sec W=10M
HEAD LOSS METERS PER 100 METERS
.25
.20
.15
.10
.05
0.00
.01
.02
.03
SMOOTH CONCRETE
EARTH,GD.COND.
EARTH W/WEEDS
FRICTION FACTOR METERS^1/6

Figure A-2

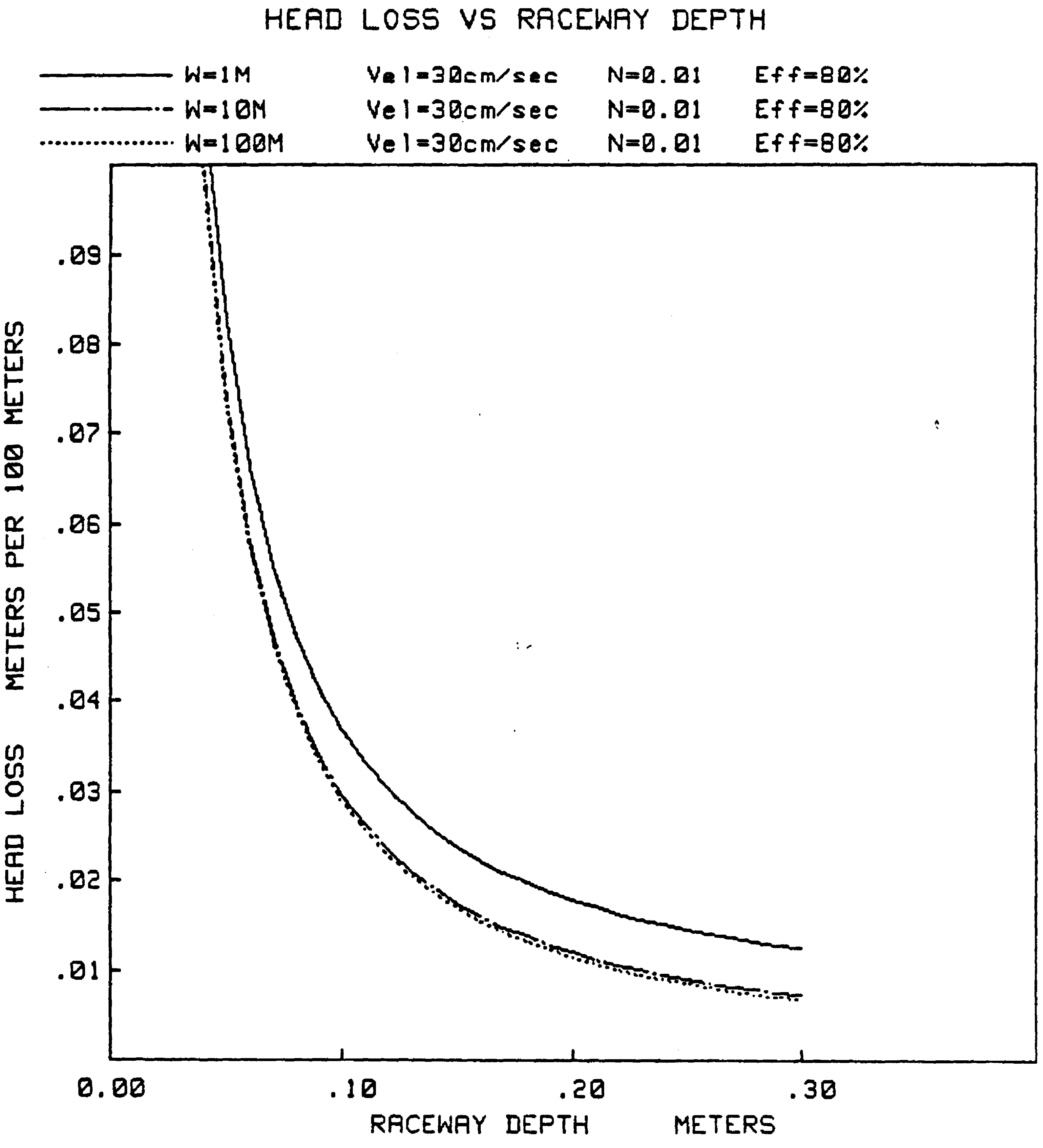

HEAD LOSS VS RACEWAY DEPTH
W=1M Vel=30cm/sec N=0.01 Eff=80%
W=10M Vel=30cm/sec N=0.01 Eff=80%
W=100M Vel=30cm/sec N=0.01 Eff=80%
HEAD LOSS METERS PER 100 METERS
.09
.08
.07
.06
.05
.04
.03
.02
.01
0.00
.10
.20
.30
RACEWAY DEPTH METERS

Figure A-3

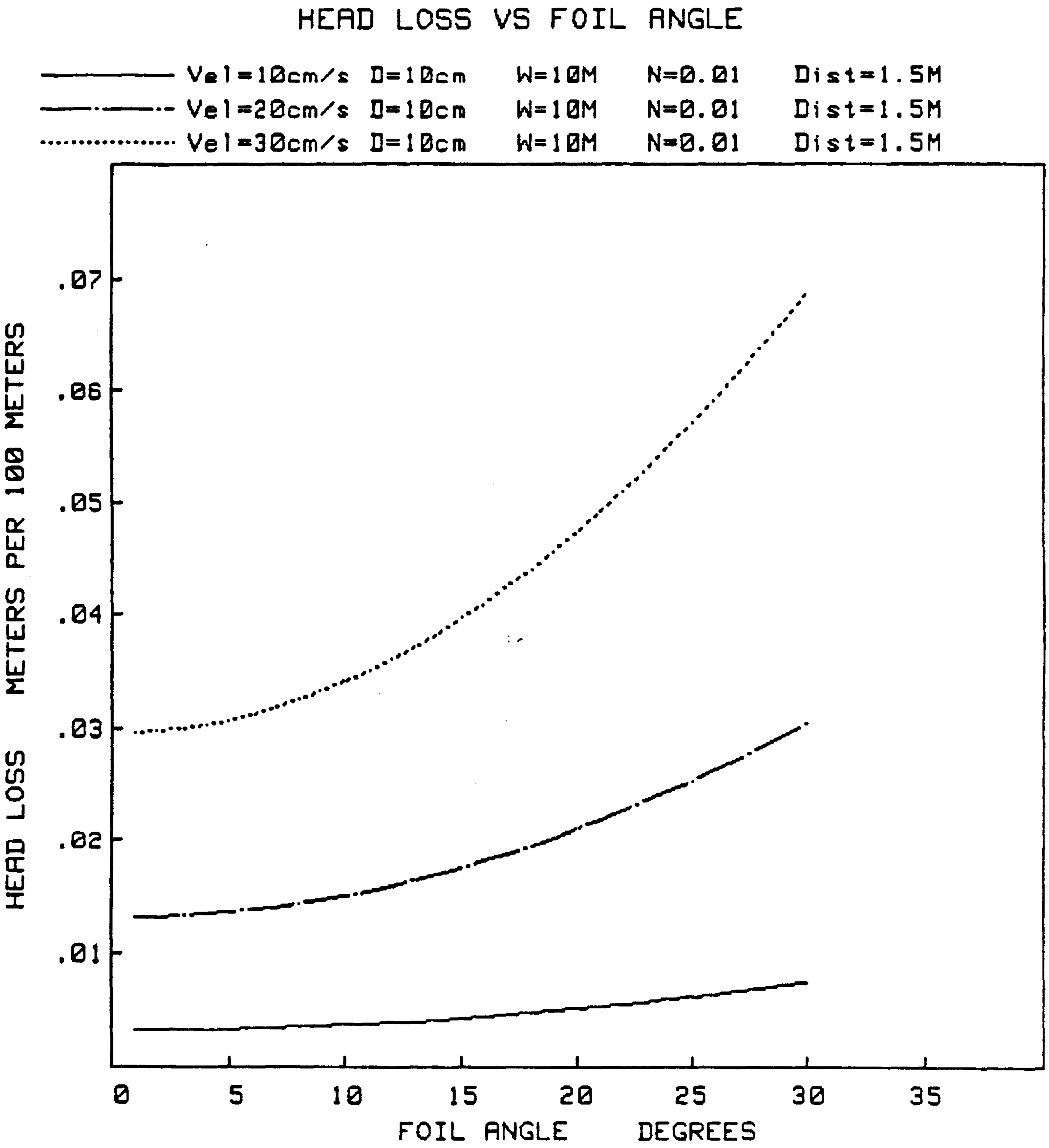

HEAD LOSS VS FOIL ANGLE
Vel=10cm/s D=10cm W=10M N=0.01 Dist=1.5M
Vel=20cm/s D=10cm W=10M N=0.01 Dist=1.5M
Vel=30cm/s D=10cm W=10M N=0.01 Dist=1.5M
HEAD LOSS METERS PER 100 METERS
.07
.06
.05
.04
.03
.02
.01
0
5
10
15
20
25
30
35
FOIL ANGLE DEGREES

Figure A-4

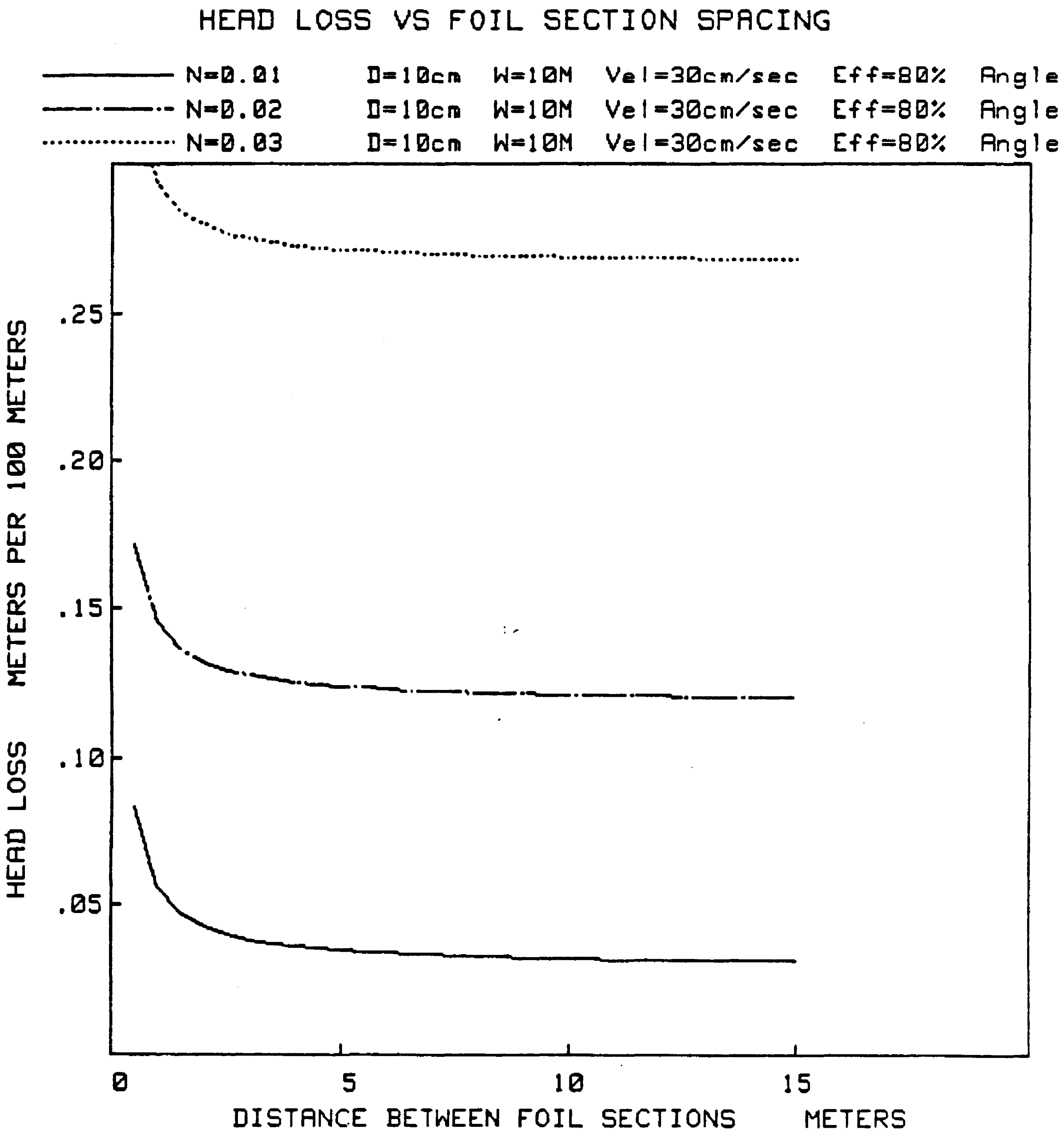

HEAD LOSS VS FOIL SECTION SPACING
N=0.01 D=10cm W=10M Vel=30cm/sec Eff=80% Angle
N=0.02 D=10cm W=10M Vel=30cm/sec Eff=80% Angle
N=0.03 D=10cm W=10M Vel=30cm/sec Eff=80% Angle
HEAD LOSS METERS PER 100 METERS
.25
.20
.15
.10
.05
0
5
10
15
DISTANCE BETWEEN FOIL SECTIONS METERS

Figure A-5

APPENDIX B

Mixing Characteristics Created by Various Shaped and Positioned Plates in Low Velocity Shallow Water Flow

Mixing Characteristics Created by Various Shaped and Positioned Plates in Low Velocity Shallow Water Flow

by

Edmond D.H. Cheng
Gordon L. Dugan
Edward K. Shikada
Andrew H. Oshita

Hawaii Natural Energy Institute
University of Hawaii at Manoa
Honolulu, Hawaii

March 1985

INTRODUCTION

The concept of using algal mass culture for numerous beneficial uses commenced in the 1950s. The early goal projected the use of algal products as important sources of inexpensive protein that would help alleviate world hunger; however, to date, for various reasons, such has not been the case.

Nevertheless, the potential range of algal mass cultures has expanded to include a source of animal protein, wastewater treatment, eutrophication control, water renovation, extractable commercial chemicals, closed life-support systems, aquaculture, and recently a renewed interest in the bioconversion of solar energy for power production. The latter involves the potential conversion of algal mass to methane, various petroleum products, and even hydrogen. On a widescale basis, however, up to the present time, the use of mass algae cultures has been primarily restricted to wasterwater treatment operations (Goldman 1978; Oswald and Beneman 1977; Shelf 1982).

Unfortunately, large-scale mass algae culturing in outdoor units has been quite limited in the United States, with the 0.67 acre culture system at the University of California at Berkeley's Sanitary Engineering Research Laboratory (Richmond, California) being the largest one constructed and operated. Thus, at best algal culturing is striving for "state of the art" status, rather than being grounded on some scientific principles.

In an algal mass culture project conducted in Honolulu, Hawaii by Professor Edward Laws (Laws, et al. 1984), the use of vanes and/or plates set an angles in the culture (marine algae) raceway appeared to increase algal production. The reason for the increase is not fully known, but could be the result of several interrelated parameters. However, it is felt that induced mixing created by the vanes and/or plates is at least a major contribution to increase algal production.

PURPOSE AND SCOPE

The purpose of the herein reported project was to ascertain the mixing characteristics and total energy created by the placement of various shaped and positioned plates in low velocity shallow water flow. The experiments were conducted in the 4 ft wide by 40 ft long tilting flume, located in the University of Hawaii at Manoa Department of Civil Engineering Hydraulic Laboratory in Holmes Hall.

These flumes are classically designed to operate at a velocity of several feet per second (ft/s), however, algal mass culture mixing velocity in raceway units is typically around 1 ft/s. It must be clearly borne in mind that a velocity reported as 1 ft/s has a wide range of accuracy. In many cases it is an estimate based on timed floating objects in the culture unit raceway.

Since the economics of utilizing algal mass cultures to produce power is considered marginal, it is important that economical methods to enhance its production be explored. Thus, the query arises as to the actual mixing characteristics of various shaped vanes and/or plates, how often they should be placed, and importantly the total energy expenditure resulting from positioning the vanes and/or plates in the raceway channel.

Specifically the project will attempt to identify the mixing characteristics and total energy relationships of utilizing combinations of three and five 4-in. squares and 4-in. triangular shaped plates at angles of 10° and 20° in a 4-in. deep simulated 4-ft wide raceway (tilting flume) at water flows of near 1.0 ft/s. It is apparent that the results of the project can only identify the actual physical characteristics of the altered water movement. Enhanced algal growth resulting from the induced currents can only be speculated until actual algal culture tests are conducted.

METHODOLOGY

The data for this experiment were obtained through the use of a row of test plates which were submerged in the flow of the tilting flume. The test flume has a channel length of 40 ft and width of 4.0 ft, with flow conditions ajustable through the use of its pump value, head gate, tail gate, and variable tilt (Figure 1). The flow and velocity conditions called for in this investigation are very near the lowest obtainable with this type of system.

The test plates were made of steel sheets, cut to 4 in. on each side, and forming rectangles and triangles. The plates, welded to thin steel rods, were made to extend above the water surface where they were mounted with clamps onto a horizontal brace and equally spaced across the width of the flume (Figures 2 and 3). This minimized drag from sources other than the plates, and also allowed flexibility in plate positioning.

A point gage, which reads to the nearest 0.001 ft and was mounted on the flume, was used to measure flow depth. For flow speed, the STREAMFLO miniature current flowmeter system by Nixon Instrumentation Ltd., shown in Figure 4, was used. The velocity measurement system is well suited for this application for the following reasons:

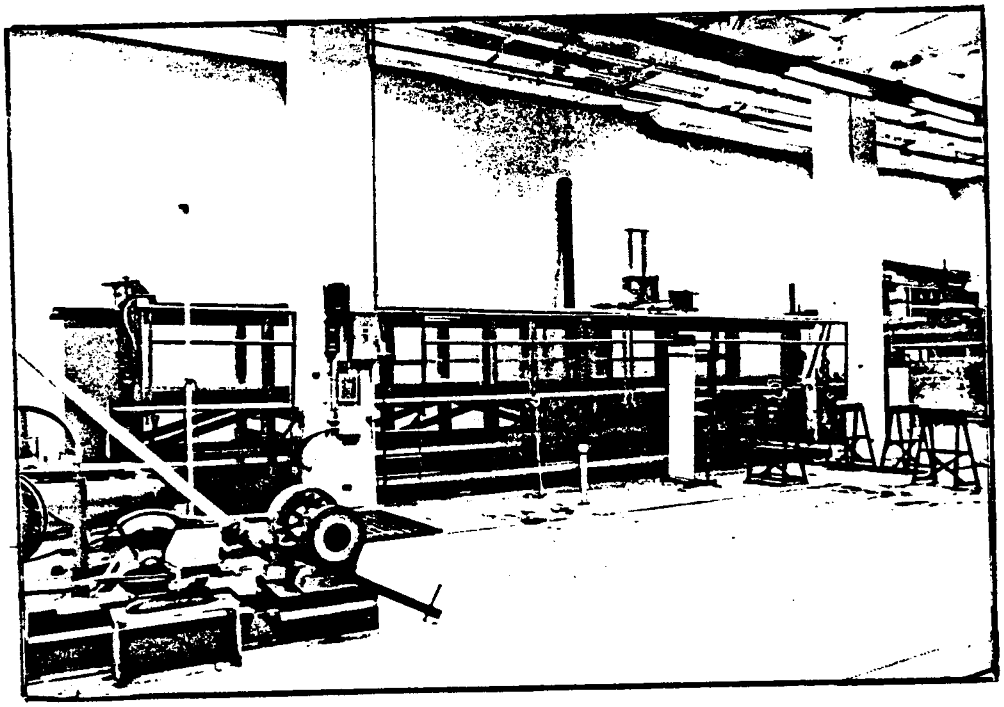


Figure 1. 4 ft. Wide by 40 ft Long Tilting Flume, Hydraulics Laboratory, University of Hawaii at Manoa

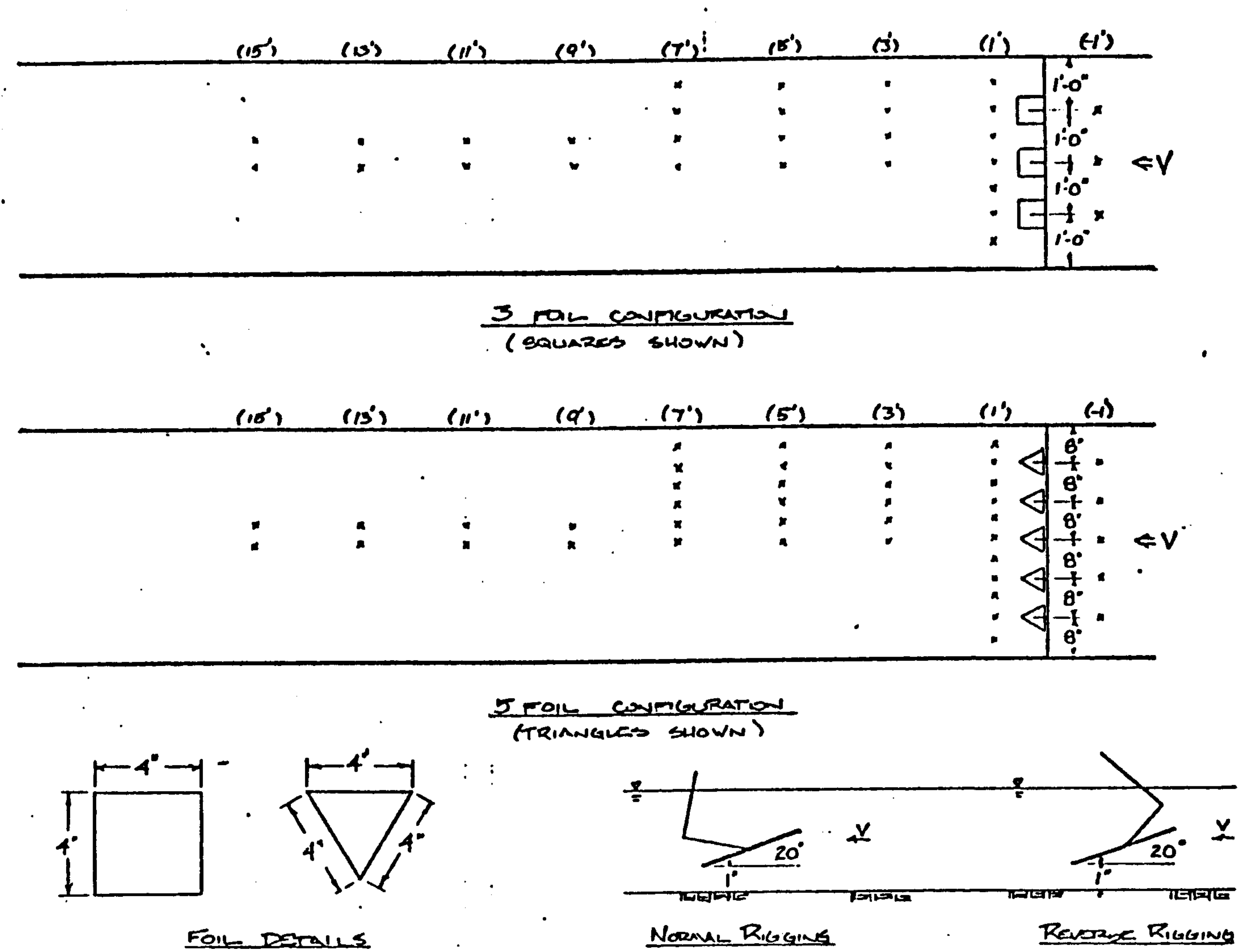


Figure 2. Typical Set-ups for Test Runs

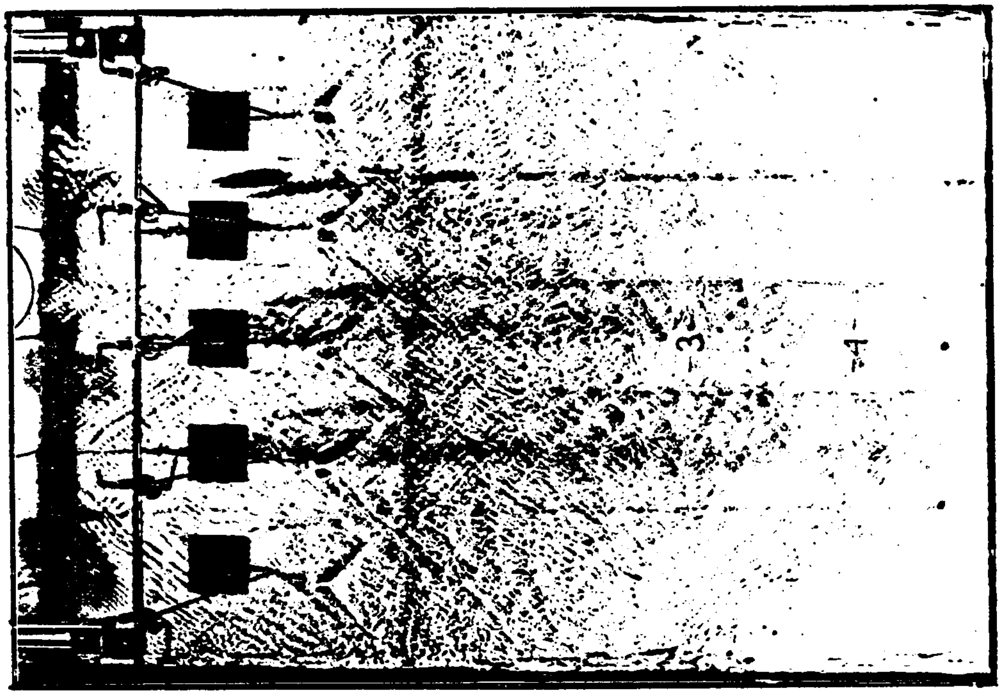
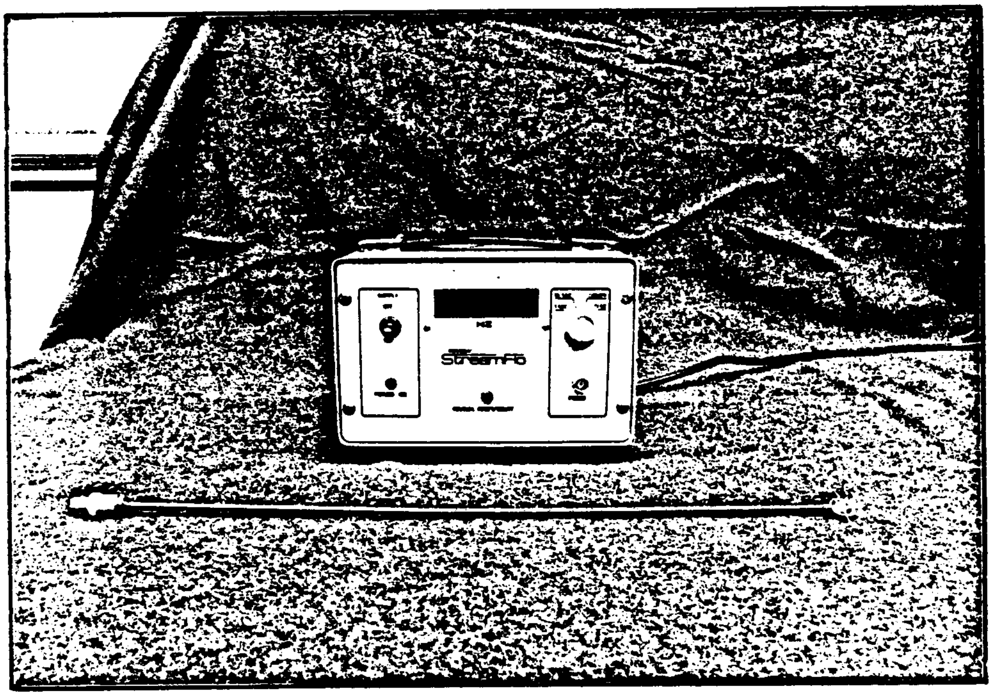
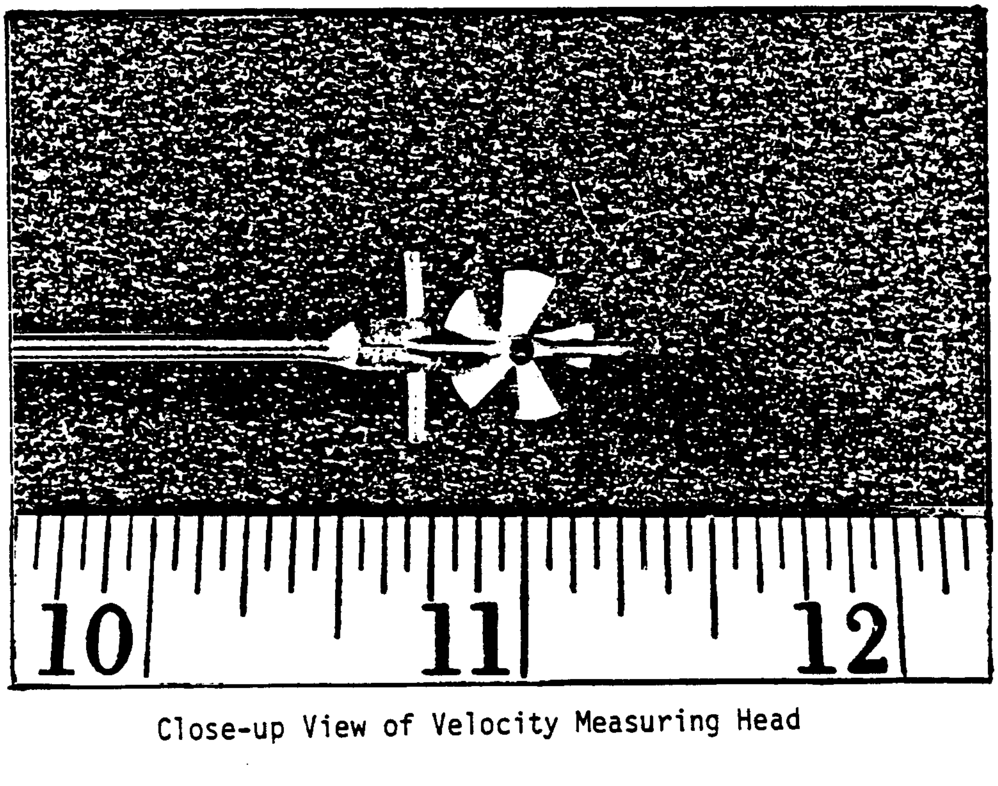


Figure 3. An Aerial View of a Typical Test Run



Current Meter and Depth Probe Velocity Indicator



Close-up View of Velocity Measuring Head

Figure 4. Streamflow Miniature Current Meter Instrument

1. At the flow speeds considered in this investigation (approximately 1 fps), the velocity probes are highly sensitive to speed differences.

2. The small measuring head (15 mm in diameter) allows measurements to be taken both very near the water surface and very near the channel bed.

3. Readings can be set for durations of 1 second, 10 seconds, or longer, thus minimizing the effects of short fluctuations in flow speed.

Prior to data collection, the velocity probe was recalibrated against a stagnation tube.

The following was used to collect data for a typical plate configuration.

After the plates were in position, the flow for a 4 in. depth was set at 1.0 ft/s which was well within an accuracy of 0.1 ft/s. Once this was achieved the pump was not shut off until all the data were recorded for the particular configuration to insure consistency of results.

For each data point the depth of flow and speed at 0.5 in., 2.0 in, and 3.5 in. above the flume bed were determined. However, at a few points the frame supporting the equipment became an obstruction, which precluded data collection at that particular point.

The number of points at which data were taken varies for the different plate configurations. For example, profiles are more detailed for configurations which were tested early in the study than for those which were tested later because once a velocity profile was documented for a single plate arrangement, subsequent arrangements were mainly examined for comparison purposes. With this in mind, primary concern was given to taking data at the following locations:

1. 1 ft upstream of each plate

2. 1 ft downstream of the plate section, both in and between the paths of the wakes

3. At 2 ft intervals, up to 15 ft downstream of the plate section where data were taken at locations directly in the wake of the center plate, and between the wakes of the center and an adjacent plate.

Six test runs were conducted in this investigation. Number and shape of the test plates, locations of measurements and basic data of velocity and depth measurements for each test run are presented in Appendix Tables A-1 through A-6.

All the test runs were conducted at a flow depth of approximately 4 in., and the undisturbed velocities established for the test runs are roughly 1.0 ft/s which is almost the lower limit of reliable speed range of the STREAMFLO miniature current flowmeter as can be observed in Appendix Figure A-1.

RESULTS AND DISCUSSION

The results of the velocity determinations for the six separate test runs at 0.5, 2.0, and 3.5 in. above the flume bed directly behind and beside each plate at incremental distances downstream of the plates (and also at 1 ft upstream of the plates for baseline comparisons) are presented in Appendix Tables A-1 through A-6.

The mean vertical velocity profile for each incremental distance at the 0.5, 2.0 and 3.5 in., based on the data from Tables A-1 through A-6, is shown graphically in subsequent figures.

The results of the Test Run No. 1, which involve the mean velocity profile at 1.0-ft increments for a distance of 7 ft downstream, and 1.0 ft upstream of five equally spaced (Figure 2)_4-in. square steel plates set at an angle of 20 is illustrated in Figure 5. As can be observed in Figure 5, the mean velocity directly behind and between the test plates is plotted together for each increment. The results can then be compared to the base condition, considered to be 1.0 ft upstream of the test plates. The dispersion effect created by the test plates can be vividly observed when dye is released upstream of the plates, as shown in Figure 6.

The velocity profiles of Test Run No. 1 (Figure 5) clearly show that for a distance of 6 ft downstream a very distinctive difference is apparent between the mean velocity directly behind the plates at the 0.5 in. depth and the mean velocity between the plates. This venturi effect creates a fluid mixing zone which is considered desirable for nutrient distribution. It is also evident in Figure 5 that for at least 7 ft downstream the mean velocity at the 0.5-in. depth is still much higher than the baseline (upstream of test plates) condition. A photographic illustration of the difference in velocity behind and between the five rectangular test plates through the use of sand distribution is shown in Figure 7.

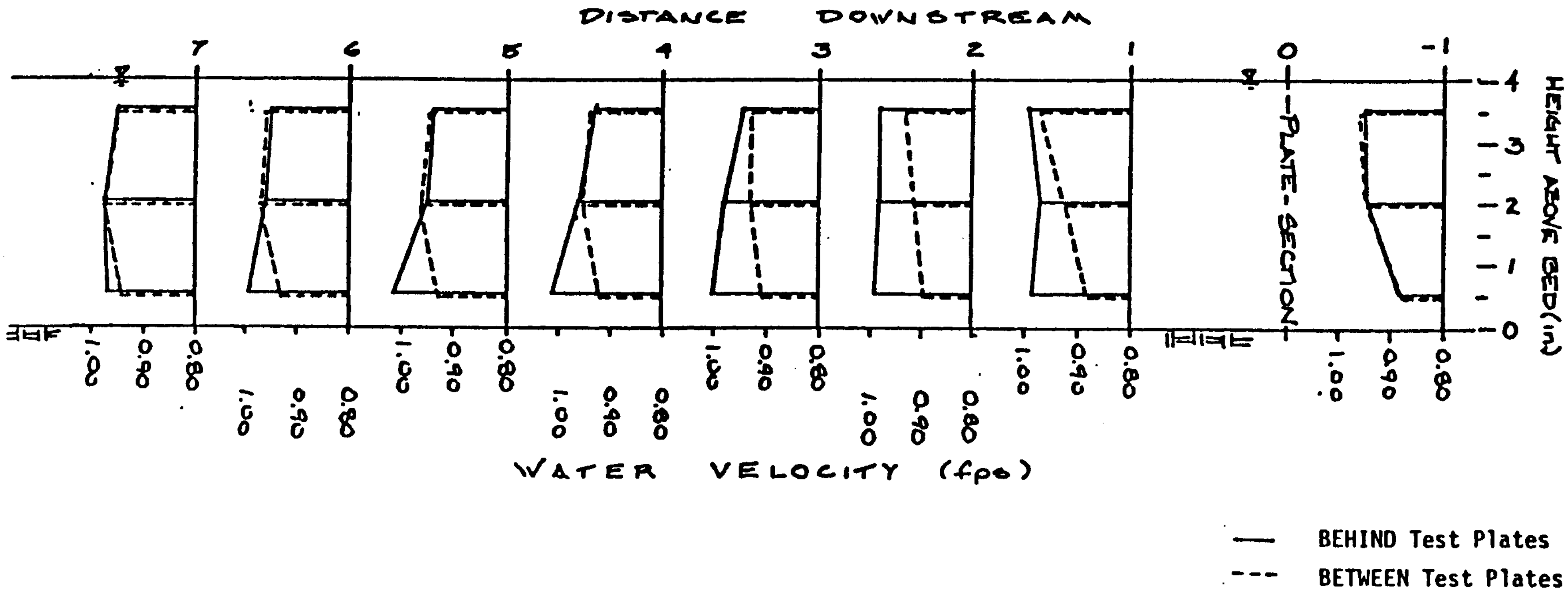


Figure 5. Mean Velocity Profiles for Test Run No. 1 - Five Square Plates at 20° Angle of Attack

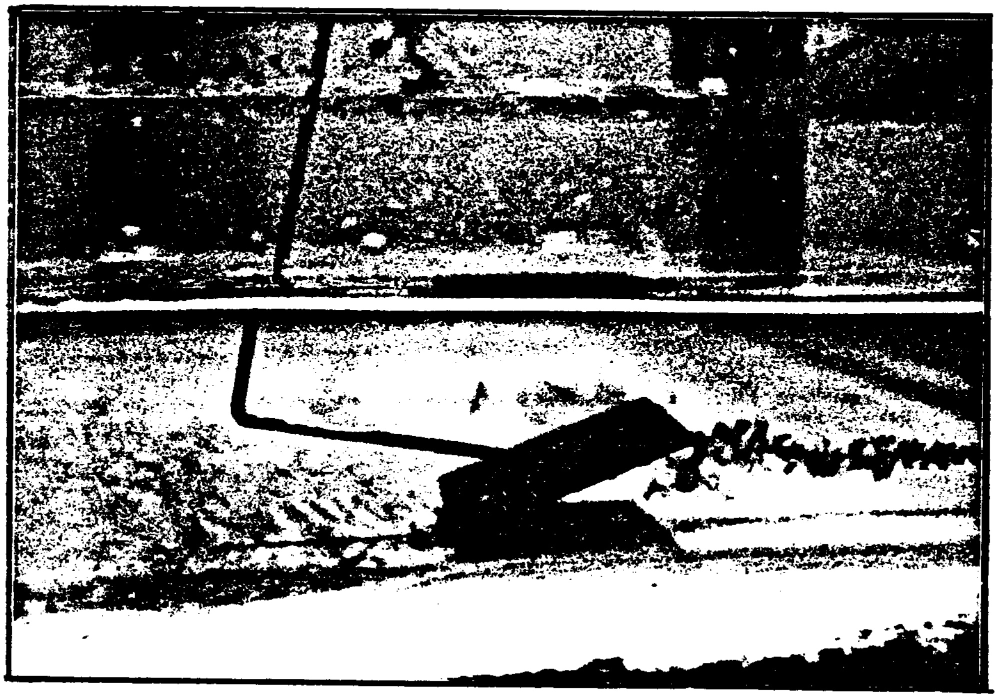


Figure 6. The Formation of a Fluid Mixing Zone Immediately After a Square Plate at 20° Angle of Attack

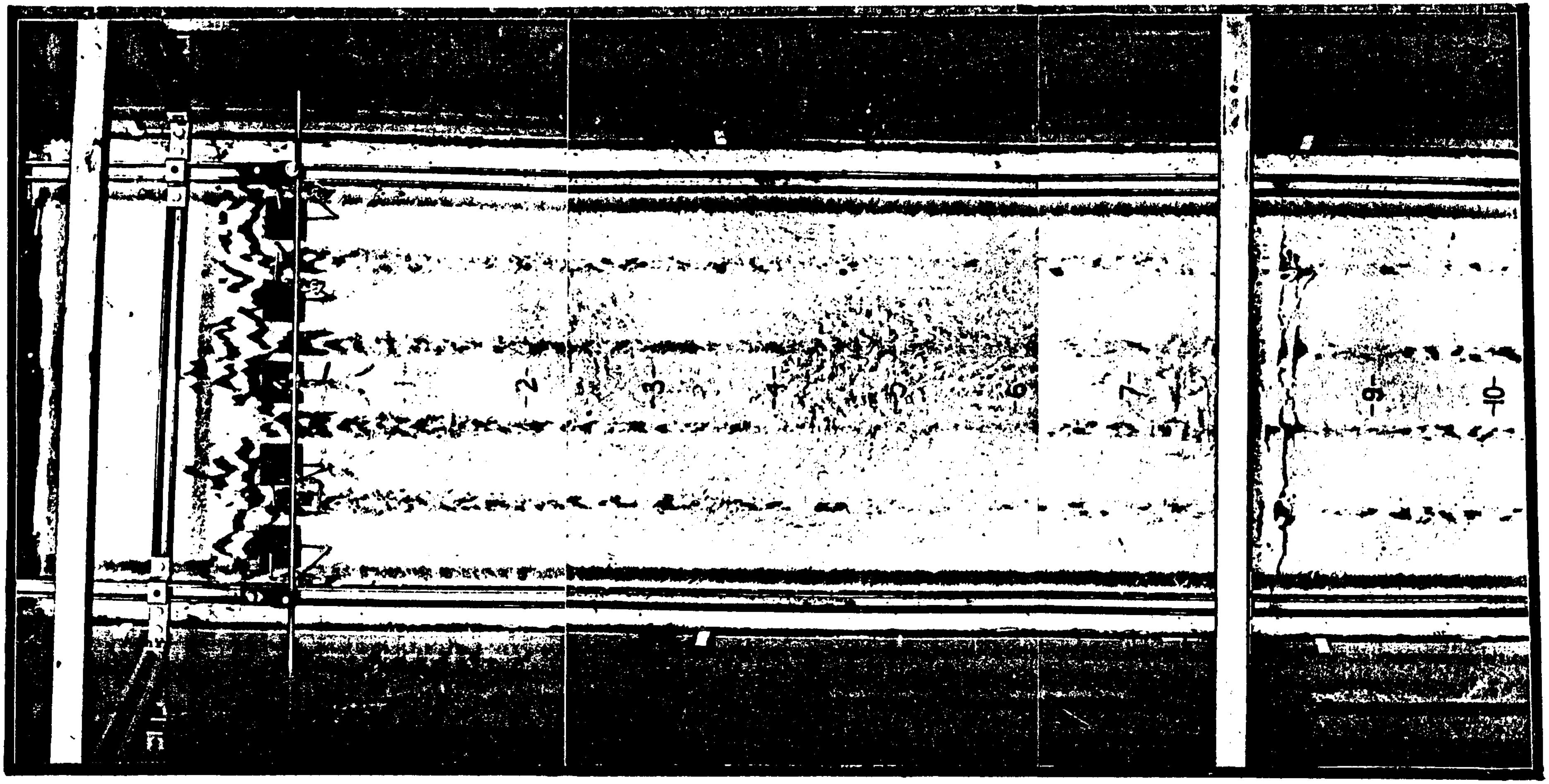


Figure 7. The Wake Zone After a Plate-Section

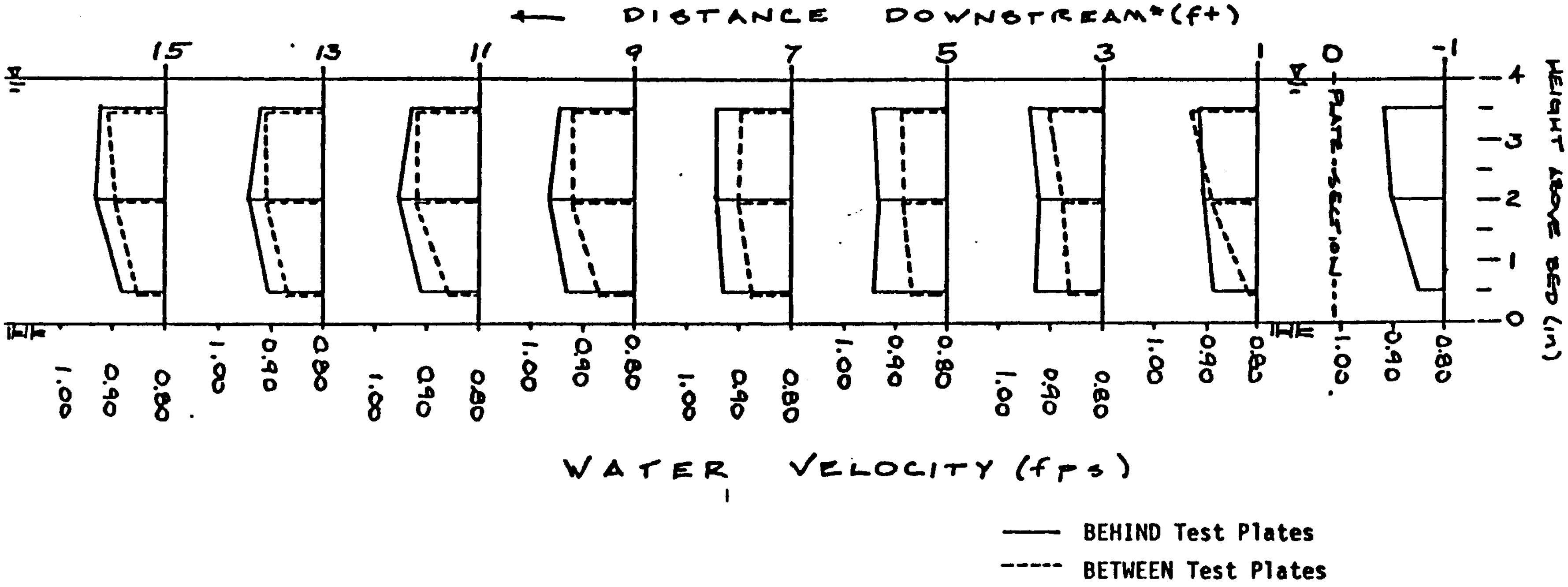
Based on the results of Run No. 1 (Figure 5), Test Run No. 2 (which is a companion of Test Run No. 1 except that 4-in. triangular plates are substituted for the square plates) was analyzed for a downstream distance of 15 ft at 2 ft incremental intervals. The mean profiles of Test Run No. 2 are presented in Figure 8. The venturi effect (and consequent fluid mixing) of the mean velocity profiles between and directly behind the test plates for up to 15 ft downstream is evident. At the 15-ft distance the 0.5 in. depth velocity behind the plates appears to still be higher than the base flow conditions, whereas, the mean velocity between the plates has returned to near normal conditions. Because of the drag on the flume bed when the 0.5-in. depth has returned to baseline conditions, the effect of the positioned plates is assumed to have lost their influence. The mean velocity profiles of Test Run No. 3, involving three equally spaced 4-in. square steel plates at a 20 angle for up to 15 ft downstream at 2 ft intervals is shown in Figure 9. The prominent venturi effect and the strong velocity at the 0.5-in. depth directly behind the test plates is quite evident. The lesser number of test plates (three vs five) undoubtably created the grater venturi effect. A photograph illustration of the wide horizontal dispersion of dye as a result of the test plates is presented in Figure 10.

Test Run No. 4, the counterpart of Test Run No. 3, except that 4-in. triangular plates were substituted for 4-in. square plates, is shown in Figure 11. The results of Test Run No. 4 are quite similar to Run No. 3 (Figure 9) except that the 0.5-in. profile does not appear as strong at the 15-ft distance.

The mean velocity profiles of Test Run Nos. 5 and 6 (Figure 12 and 13, respectively) can be respectively compared to Test Runs 1 and 2 (Figures 5 and 8) except that the angle of the plates was set at 10 rather than 20 . For the rectangular plate conditions (Figures 5 and 12), the 20 angle maintains a higher 0.5 in. depth velocity in comparison to baseline conditions than observed for the 10 angle. However, when comparing the results for the triangular shape (Figures 8 and 13) the difference between the 10 and 20 angle is not particularly distinctive.

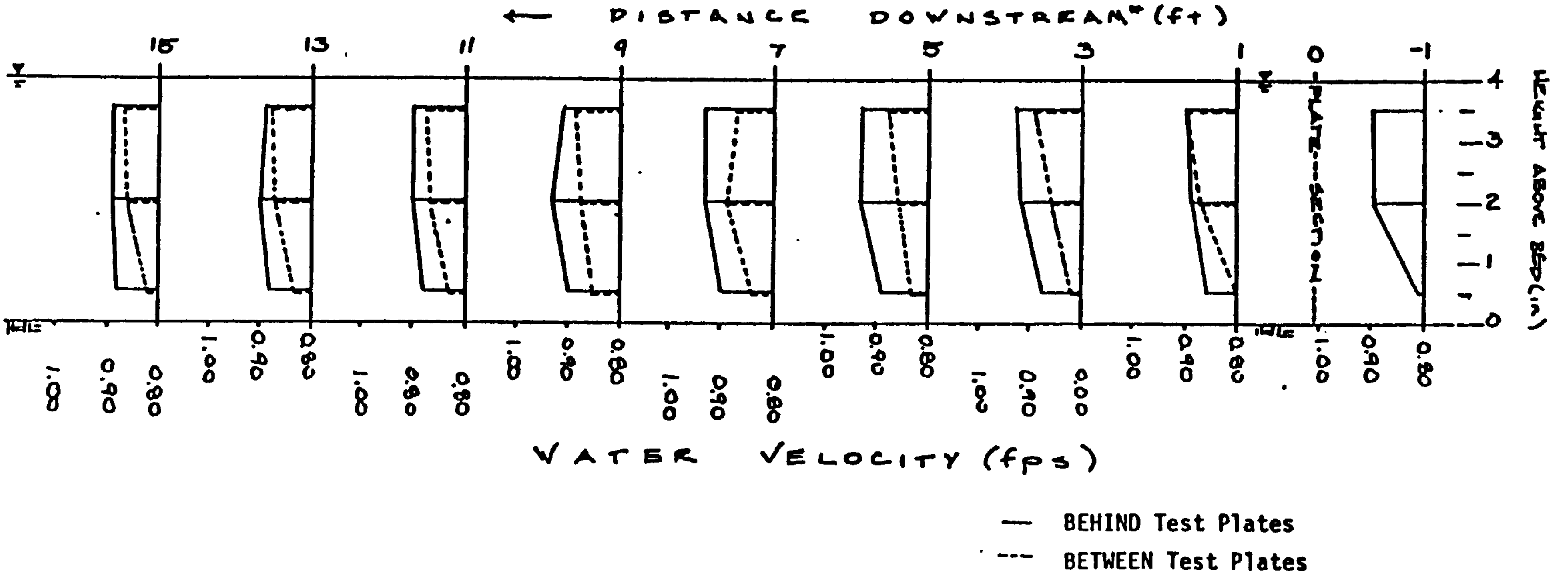
Based on the foregoing, it appears that a higher degree of apparent mixing occurred for Test Run No. 3, which utilized three 4-in. steel plates at an angle of 20 (Figure 9).

The basic equations for the surface water flow determination parameters (drag force; Manning's roughness coefficient, n; energy profile; and velocity profile) are presented in Appendix Table A-7. The results of these determinations for Test Runs 1 through 6 are respectively presented in Appendix Tables A-8 through A-13.



* NOTE DISTORTED SCALE UPSTREAM OF PLATES

Figure 8. Mean Velocity Profiles for Test Run No. 2 - Five Triangular Plates at 20° Angle of Attack



* NOTE DISTORTED SCALE UPSTREAM OF PLATES

Figure 9. Mean Veloicty Profiles for Test Run No. 3 - Three Square Plates at 20° Angle of Attack

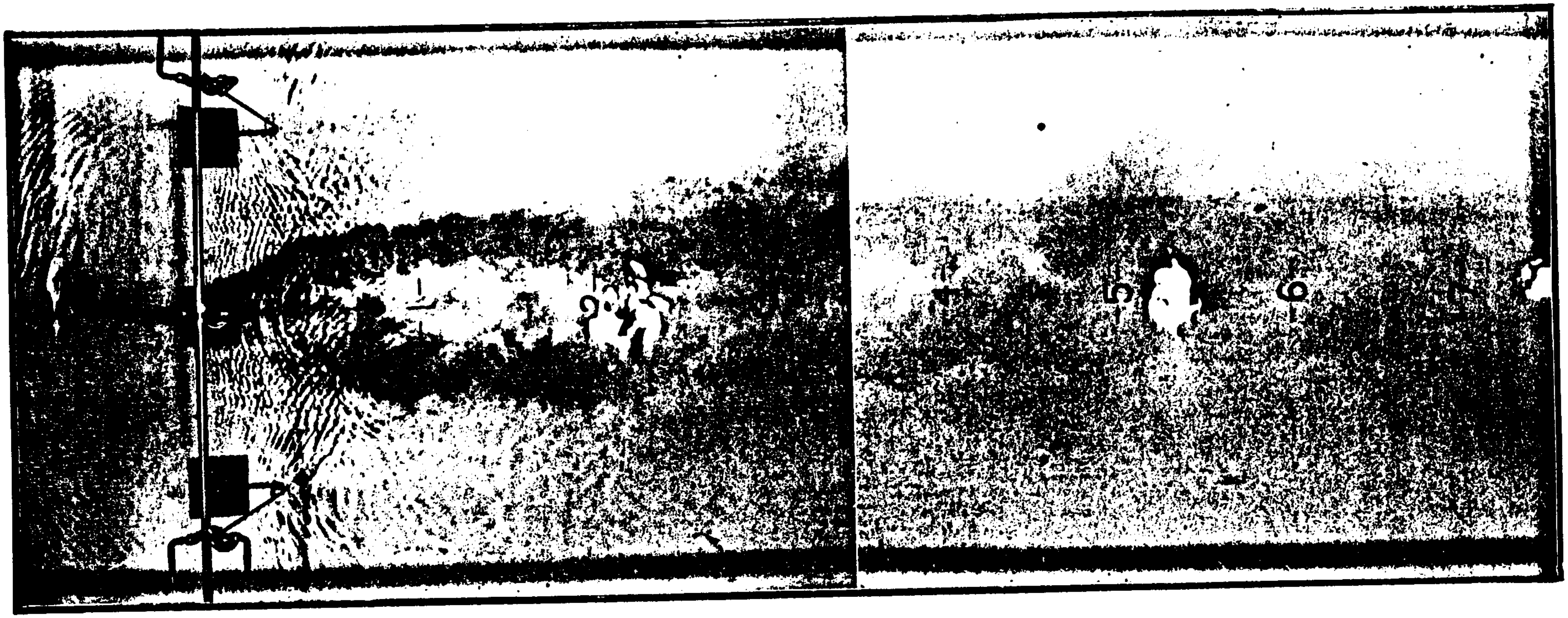


Figure 10. Flow Dispersion After a Plate-Section

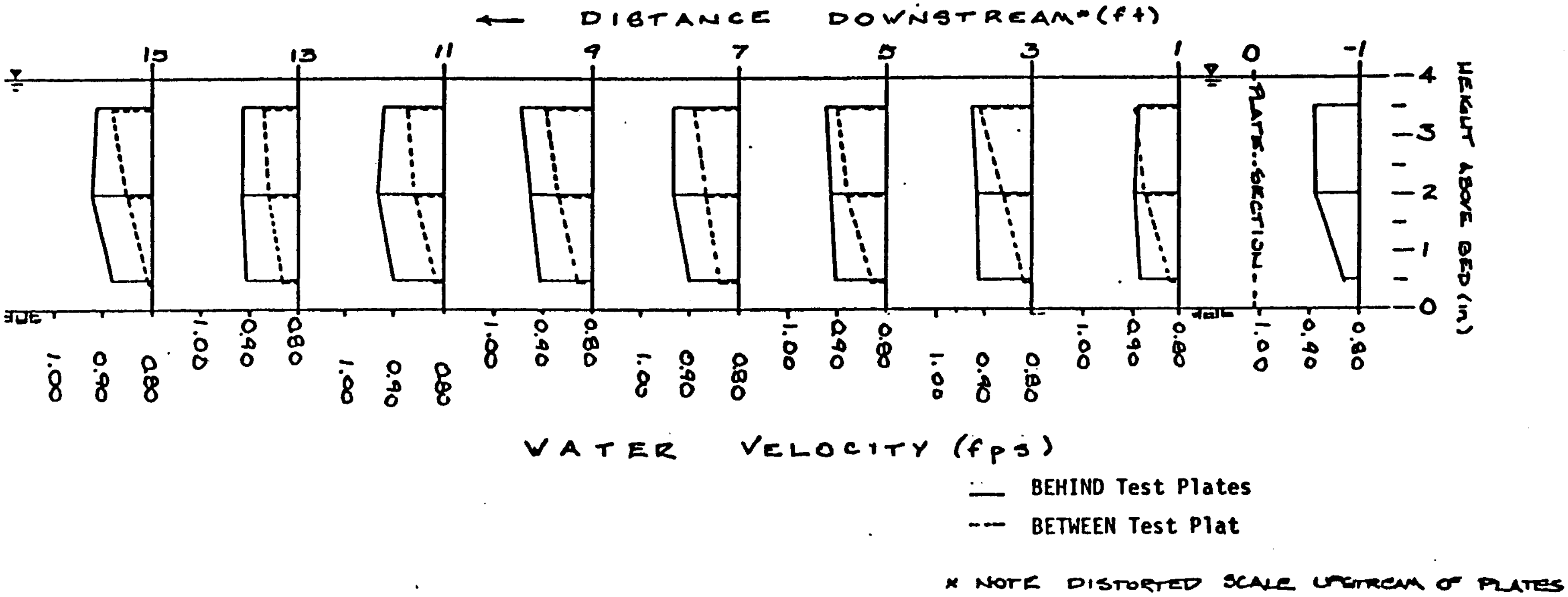


Figure 11. Mean Velocity Profiles for Test Run No. 4 - Three Triangular Plates at 20° Angle of Attack

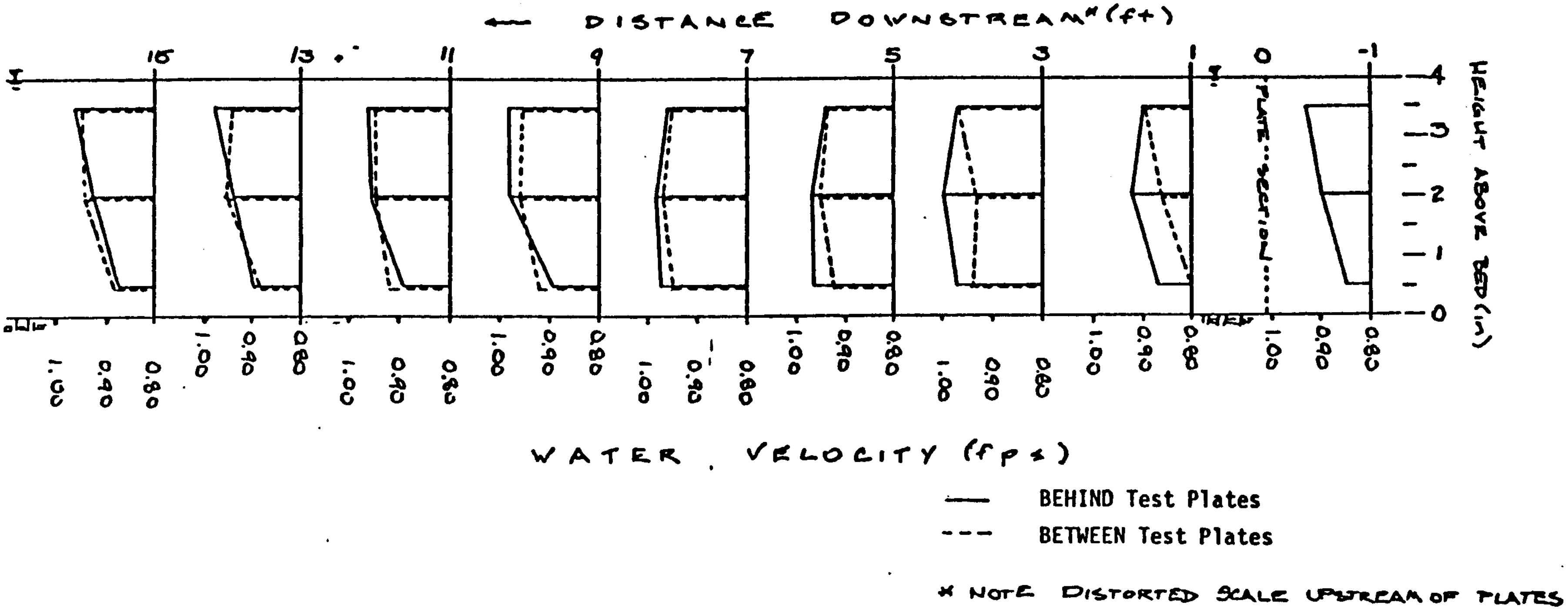


Figure 12. Mean Velocity Profiles for Test Run No. 5 - Five Square Plates at 10° Angle of Attack

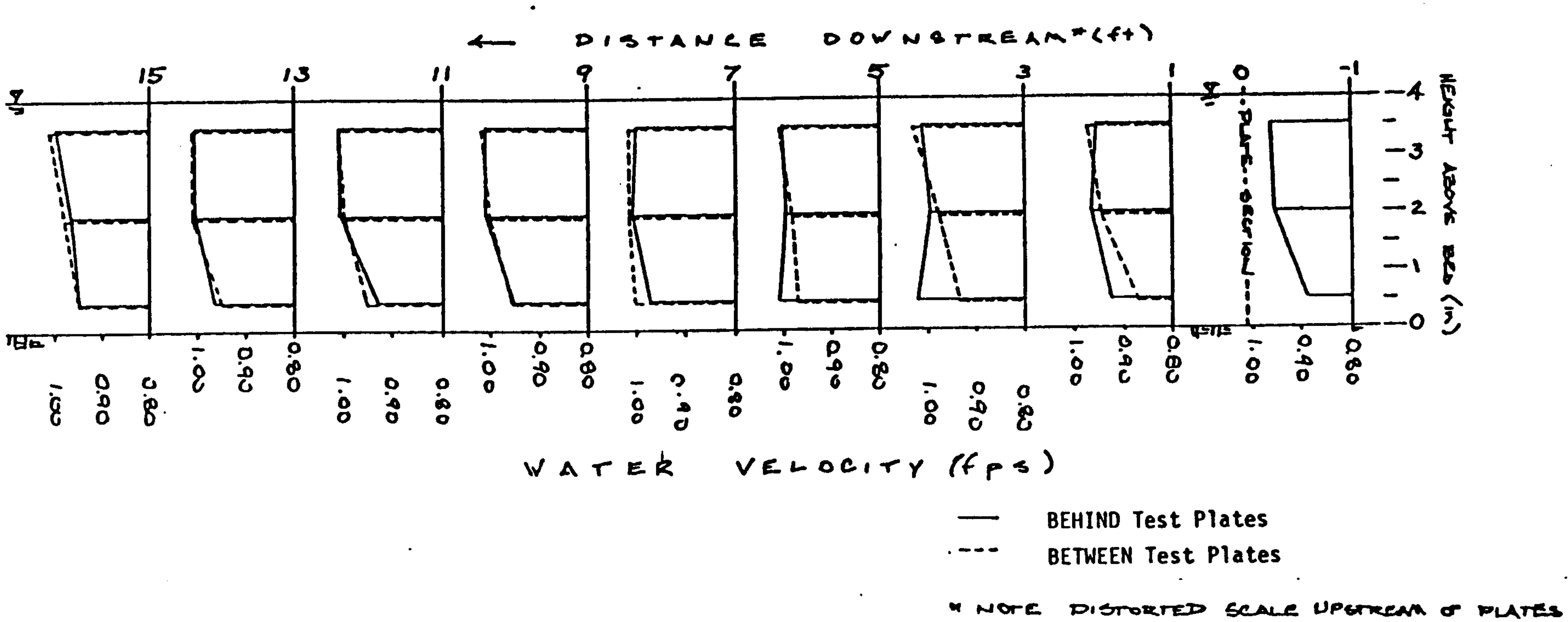


Figure 13. Mean Velocity Profile for Test Run No. 6 - Five Triangular Plates at 10° Angle of Attack

The total energy results, based on the mean velocity at each incremental distance (from Tables A-8 through A-13), are summarized in Table 1. As can be noted, the indicated energy loss between the plate section and a section 15 ft downstream is less than 0.02 ft which is an insigificant level of energy loss in the relatively tranquil flow conditions.

The mean drag forces for the six test runs that were determined and presented in Appendix Table A-8 through A-13 are summarized in Table 2. As can be observed, the apparent impact of the fluid on the plates is relatively insignificant regardless of the plate shapes or angles of attack.

CONCLUSIONS

Results of the tests lead to the following conclusions:

1. As indicated in the six test runs, at an elevation of 5 in. above the flume bed, the velocities behind the test plates are consistently higher than those between test plates for up to 15 ft downstream. Therefore, immediately after the test plate section, a fluid mixing zone is formed (Figure 6). This venturi effect created a desirable mixing condition.

2. The velocity profiles measured between plates of the six test runs also indicated that up to 5 ft or so downstream from the test plates, the flows are retarded to some extent and flow dispersion took place (Figure 10). This phenomenon may be attributable to the turbulence created at the plate section. However, the flow regains its form at a distance of 7 to 15 ft downstream from the plate section.

3. The results of conclusions 1 and 2 indicate that a series of test plates placed at approximately 10-to-[illegible]-ft intervals would be sufficient to promote the desired mixing condition.

4. As indicated in Table 1, the energy loss between the plate section and a section 15 ft downstream is less than 0.02 ft, which is an insignificant level of energy loss in the relatively tranquil flow conditions. However, as observed from Figure 7, an apparent wake zone is achieved downstream of the plate section.

TABLE 1

Total Ergy Relationship for Various Shaped Plateand Angles in Shallow Stream Flow

	DISTANCE FROM PLATES (ft)	TOTAL ENERGY (FT)					
		Test Run No.*					
		1	2	3	4	5	6
Upstream (-)	-1	0.353	0.384	0.375	0.375	0.362	0.366
Downstream (+)	1	0.361	0.382	0.375	0.374	0.360	0.363
	2	0.360					
	3	0.365	0.378	0.368	0.365	0.359	0.361
	4	0.353					
	5	0.348	0.361	0.362	0.362	0.352	0.361
	6	0.341					
	7	0.334	0.363	0.358	0.357	0.346	0.349
	8						
	9		0.365	0.357	0.354	0.342	0.348
	10						
	11		0.374	0.366	0.364	0.360	0.359
	12						
	13		0.381	0.374	0.371	0.360	0.366
	14						
	15		0.391	0.383	0.379	0.365	0.370

*Test Run No.	No., be, and Angle of Plates with Flow
1	Five 4n. squares @ 20°
2	Five 4n. triangles @ 20°
3	Three-in. squares @ 20°
4	Three-in. triangles @ 20°
5	Five 4n. squares @ 10°
6	Five 4n. triangles @ 10°

TABLE 2

Drag Forces for Various Shaped Plates at Angles in Shallow Stream Flow

TEST RUN		
No.	Plate No Shape and Angle	F_D ($^{lb}/_{Plate}$)
1	5 Sq@ 20°	0.0468
2	5 TR@ 20°	0.0190
3	3 Sq@ 20°	0.0418
4	3 TR 20°	0.0186
5	5 Sq 10°	0.0222
6	5 TR 10°	0.0093

* 4-in. Square plat, refer to Figure 2.

\+ 4-in. Triangle plates, refer to Figure 2.

5. Drag forces on plates of each test run are summarized in Table 2. The impact of fluid on the plates is relatively insignificant regardless of plate shapes or angles of attack.

6. The results of the six test runs, coupled with the photographs on Figure 7 and 10, clearly indicate that a spacing of three 4-in. plates across the 4-ft channel provides adequate mixing in comparison with the use of five plates.

7. No particular changes of total energy were observed due to different combinations of plate shapes or number of test plates in the test runs, when positioned at different angles of attack (that is 10 or 20).

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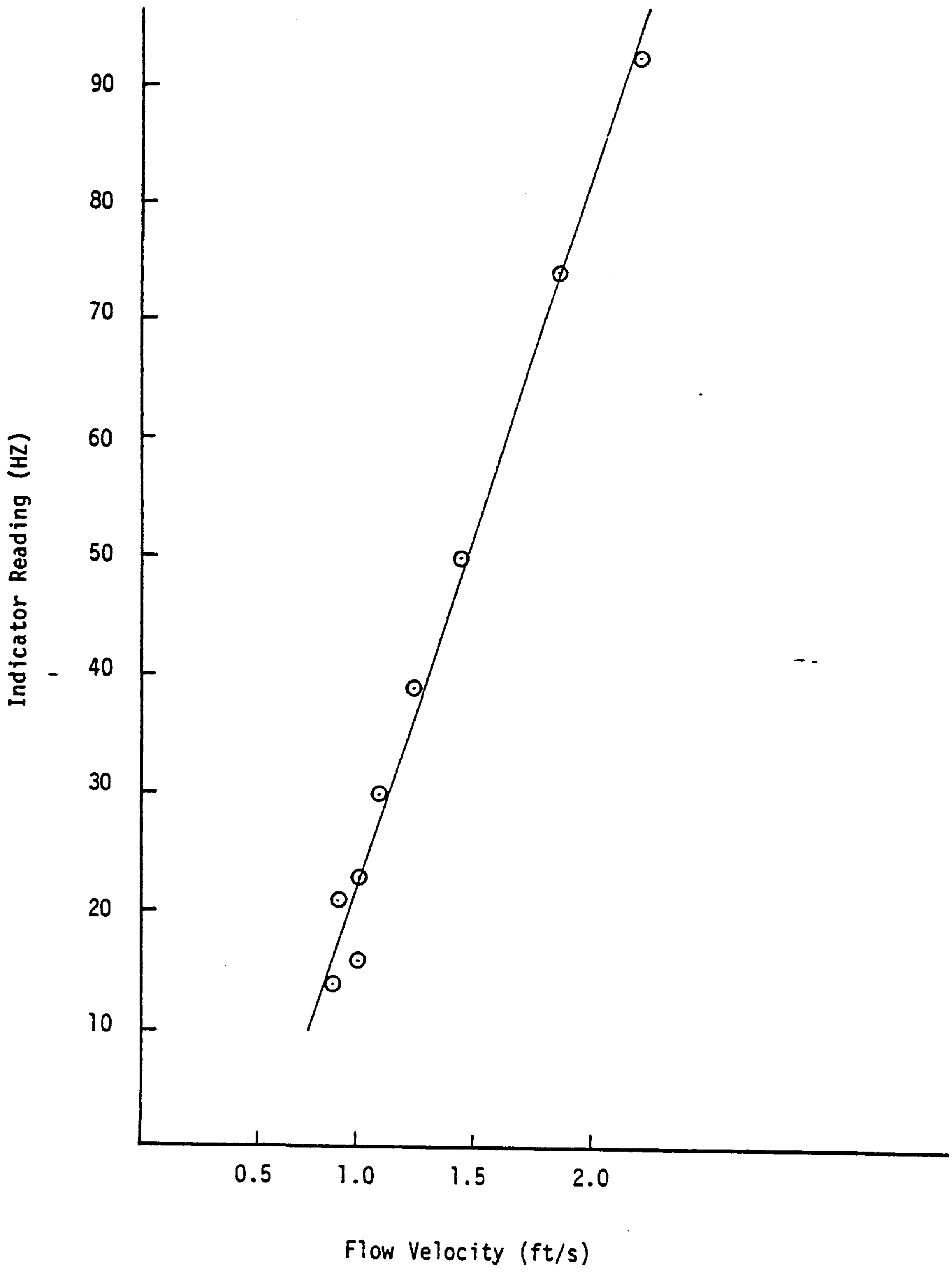


Figure A-1 Cabration Curve of the Miniature Current Flowmeter

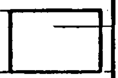
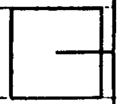
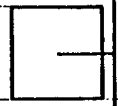
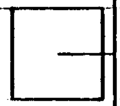
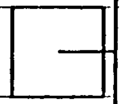
3.5 . |0.97 |0.96 |0.94 |0.92 |0.92 |0.95 |0.97 | | || |0.95 |(C)

TABLE A-1

Test Run No. 1

Five 4-in Squares @ 20°*

November 18, 198

Velocity Prob depth above Slume depth in.	Water Flow																	
	DOWNSTREAM SECTIONS														FOIL SECTION	UPSTREAM		Plate Position in 4-ft Channel Width
	7 ft		6 ft		5 ft		4 ft		3 ft		2 ft		1 ft			1 ft		
	Vel.	depth	vel.	depth	Vel.	depth	Vel.	depth	Vel.	depth	Vel.	depth	Vel.	depth		Vel	depth	(1)
	ft/sec	in.	ft/sec	in.	ft/sec	in.	ft/sec	in.	ft/sec	in.	ft/sec	in.	ft/sec	in.		ft/sec	in.	
2.0	0.99		0.98		0.97		0.96		0.95		0.91		0.95			0.95		(2)
0.5	0.95		0.95		0.96		0.97		0.98		0.98		0.96			0.89		
3.5	0.97		0.97		0.96		0.95		0.93		0.94		1.00			0.96		(3)
2.0	0.99		0.98		0.97		0.95		0.94		0.91		0.92			0.94		
0.5	0.94		0.94		0.94		0.93		0.92		0.90		0.88			0.87		
3.5	0.96		0.95		0.92		0.91		0.93		0.98		0.97			0.95		(4)
2.0	0.96		0.94		0.94		0.97		0.99		1.01		0.98			0.93		
0.5	0.98		1.00		1.02		1.02		1.01		1.01		0.99			0.87		
3.5	0.95		0.97		0.96		0.95		0.93		0.92		0.95 fps			0.97		(5)
2.0	0.97		0.97		0.97		0.95		0.93		0.92		0.93	0.332'		0.94		
0.5	0.95		0.94		0.93		0.93		0.92		0.92		0.89			0.88		
3.5	0.96		0.95		0.94		0.94		0.96		0.98		1.00 fps			0.96		(6)
2.0	0.97	0.329	0.95	0.328	0.94	0.333	0.96	0.332	0.97	0.339	0.97	0.336	0.98	0.338'		0.94	0.325	
0.5	0.98		0.99		0.99		1.02		1.00		1.00		0.98			0.85		
3.5	0.97		0.98		0.96		0.90		0.92		0.91		0.96 fps			0.96		(7)
2.0	0.97		0.98		0.98		0.96		0.93		0.90		0.91	0.343'		0.94	0.335	
0.5	0.93		0.93		0.93		0.93		0.93		0.90		0.88			0.95		
3.5	0.96		0.96		0.95		0.94		0.98		1.02		1.00 fps			0.96		(8)
2.0	0.97		0.95		0.94	0.336	0.96	0.342	1.00	0.340	1.00	0.343	0.99	0.345'		0.95	0.331	
0.5	0.97		0.97		1.00		1.01		1.00		0.99		0.98			0.91		
3.5	0.95		0.96		0.95		0.94		0.93		0.92		0.97 fps			0.96		(9)
2.0	0.98	0.317	0.98	0.333	0.96	0.337	0.95	0.345	0.94	0.345	0.91	0.348	0.89	0.354'		0.93	0.331	
0.5	0.93		0.91		0.90		0.90		0.89		0.89		0.86			0.89		
3.5	0.92		0.93		0.93		0.94		0.97		0.97		0.99 fps			0.93		(10)
2.0	0.96	0.312	0.97	0.317	0.97	0.321	0.97	0.323	0.99	0.323	1.00	0.333	0.96	0.335'		0.91	0.336	
0.5	0.98		1.00		1.01		1.02		1.00		0.99		0.97			0.87		
3.5	0.97		0.91		0.93		0.94		0.95		0.97		0.97 fps					(11)
2.0	0.96	0.307	0.96	0.310	0.94	0.320	0.93	0.322	0.92	0.331	0.91	0.333	0.97	0.335'				
0.5	0.95		0.94		0.96		0.93		0.91		0.87		0.89					

* Refer to Figure 2

Slope = 0.00052
n = 0.0160

3 | 0.90 | 0.88 | 0.90 | 0.95

TABLE A-2
Test Run No. 2
Five 4-in Triangles @ 20°C *

[Same foremat as Table A-1]

DATE: Nov. 24, 1984

Depth	DOWNSTREAM SECTIONS								FOIL SECT.	UPSTREAM	
	15 ft	13 ft	11 ft	9 ft	7 ft	5 ft	3 ft	1 ft		1 ft	
3					0.89	0.91	0.90	0.91		Average Depth	
2					0.90	0.88	0.87	0.88		= 0.363	(1)
1					0.89	0.87	0.85	0.82			
3					0.93	0.93	0.93	0.90		0.92 fps	
2					0.93 0.342	0.93 0.350	0.91 0.359	0.90 0.370	◁	0.89 0.367'	(2)
1					0.92	0.92	0.92	0.89		0.86	
2					0.90 0.342	0.89 0.349	0.86 [illegible]	0.87 0.365			(3)
1					0.89	0.87	0.87	0.83			
3					0.94	0.95	0.95	0.94		0.93	
2					0.94 0.345	0.92 0.349	0.93 0.361	0.91 0.368	◁	0.92 0.366'	(4)
1					0.94	0.95	0.94	0.90		0.86	
3	0.91	0.91	0.92	0.92	0.91	0.89	0.91	0.95			
2	0.90 0.377	0.91 0.365	0.92 0.359	0.92 0.347	0.91 0.348	0.89 0.353	0.87 0.356	0.91 0.359			(5)
1	0.85	0.87	0.85	0.87	0.87	0.87	0.86	0.82			
3	0.92	0.92	0.93	0.94	0.94	0.95	0.95	0.91		0.95	
2	0.93 0.379	0.94 0.369	0.95 0.359	0.96 0.351	0.95 0.353	0.94 0.354	0.93 0.358	0.92 0.360	◁	0.93 0.363'	(6)
1	0.88	0.90	0.91	0.93	0.94	0.94	0.93	0.91		0.86	
3								0.95			
2								0.91 0.364			(7)
1								0.83			
3								0.94		0.93	
2								0.93 0.362	◁	0.93 0.365'	(8)
1								0.89		0.87	
3								0.91			
2								0.88 0.362			(9)
1								0.82			
3								0.86		0.88	
2								0.86 0.361	◁	0.85 0.355'	(10)
1								0.82		0.82	
3								0.88			
2								0.86 0.358			(11)
1								0.78			

← DIRECTION OF FLOW

Slope = 0.00052
n = 0.0174

* Refer to Figure 2

0.362 | 0.361 | 0.337 | 0.89 0.332 | 0.86 0.342 | 0.86 0.350 | 0.87 0.357

(Same format as Table A-2)

TABLE A-3
Test Run No.3
Three 4-in squares @ 20ft

~~[illegible]~~ Nov. 24/84

Depth	DOWNSTREAM SECTIONS 15 ft	13 ft	11 ft	9 ft	7 ft	5 ft	3 ft	1 ft	Foil Sect.	Upstream 1 ft	
2 1		0.85 [illegible]	0.85 [illegible]	0.87 [illegible]	0.87 0.85	0.88 0.85	0.88 0.83	0.89 0.80			(1)
3 2 1		0.89 0.361	0.89 0.348	0.90 0.338	0.92 0.93 0.334 0.91	0.93 0.92 0.341 0.89	0.93 0.92 0.350 0.89	0.92 0.89 0.359 0.87		0.91 0.90 0.360 0.84	(2)
3 2 1	0.87 0.86 0.372 0.82	0.88 0.87 0.360 0.82	0.88 0.87 0.348 0.83	0.89 0.88 0.340 0.83	0.87 0.89 0.340 0.82	0.87 0.85 0.343 0.82	0.90 0.85 0.350 0.79	0.92 0.88 0.356 0.81			(3)
3 2 1	0.8? 0.89 0.369 0.88	0.89 0.90 0.363 0.89	0.90 0.90 0.353 0.89	0.91 0.93 0.346 0.90	0.93 0.93 0.343 0.90	0.93 0.93 0.348 0.89	0.93 0.92 0.353 0.89	0.89 0.90 0.357 0.87		0.91 0.90 0.353 0.83	(4)
3 2 1		0.62 0.361	0.82 0.355	0.83 0.347	0.82 0.348	0.81 0.348	0.79 0.352	0.91 0.87 0.352 0.80			(5)
3 2 1		0.87 0.360	0.87 0.354	0.89 0.345	0.90 0.348	0.89 0.348	0.87 0.346	0.88 0.88 0.352 0.84		0.88 0.89 0.352 0.77	(6)
3 2 1		0.81	0.81	0.85	0.85	0.85	0.86	0.87 0.84 0.80			(7)

← DIRECTION OF FLOW

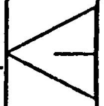
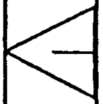
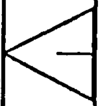
Slope = 0.00052
n = 0.0186

* Refer to Figure 2

Same format as Table A-2

TABLE A-4
Test Run No. 4
Three 4-in Triangles @ 20°C*

Nov 24, 84

[illegible]	DOWNSTREAM SECTIONS								FOIL SECT.	UPSTREAM	
	15 ft	13 ft	11 ft	9 ft	7 ft	5 ft	3 ft	1 ft		1 ft	
3					0.90	0.89	0.90	0.90			
2					0.87 0.339	0.87 0.348	0.86 0.352	0.87 0.365			(1)
					[illegible]	[illegible]	[illegible]	[illegible]			
3					0.93	0.92	0.92	0.90		0.91	
2					0.93 0.335	0.91 0.339	0.91 0.336	0.89 0.345		0.91 0.358	(2)
1					0.90	0.90	0.91	0.88		0.84	
3	0.88	0.87	0.87	0.89	0.88	0.91	0.92	0.91			
2	0.85 0.367	0.86 0.360	0.86 0.350	0.87 0.337	0.87 0.342	0.88 0.345	0.86 0.250	0.88 0.357			(3)
1	0.81	0.83	0.82	0.83	0.82	0.82	0.83	0.84			
3	0.91	0.91	0.92	0.94	0.92	0.92	0.92	0.89		0.91	
2	0.92 0.366	0.91 0.355	0.93 0.349	0.92 0.340	0.93 0.343	0.90 0.348	0.91 0.351	0.90 0.354		0.90 0.356	(4)
1	0.88	0.90	0.90	0.90	0.90	0.90	0.90	0.87		0.84	
3								0.90			
2								0.89 0.354			(5)
1								0.83			
3								0.86		0.87	
2								0.87 0.356		0.87 0.351	(C)
1								0.86		0.82	
3								0.85			
2								0.82			(7)
1								0.79			

← DIRECTION OF FLOW

Slope = 0.00052
n = 0.0174

* Refer to Figure 2.

0.84 | 10° | 0.85

TABLE A-5
Test Run No. 5
Five 4-in. Squares @ 10° *

(Same format as Table A-1)

December 15, 1994

	DOWNSTREAM SECTIONS								FOIL SECT.	UPSTREAM 1 ft	
	15 ft	13 ft	11 ft	9 ft	7 ft	5 ft	3 ft	1 ft			
3								0.85			
2								0.83 0.340			(1)
1								0.79			
3								0.88		0.87	
2								0.87 0.342		0.85 0.344	(2)
3								0.92			
2								0.87 0.345			(3)
1								0.74			
3								0.93		0.96	
2								0.98 0.344		0.96 0.342	(4)
1								0.92	10°	0.93	
3	0.95	0.94	0.95	0.95	0.95	0.94	0.97	0.99			
2	0.94 0.354	0.95 0.349	0.95 0.352	0.96 0.325	0.97 0.326	0.95 0.333	0.93 0.338	0.95 0.343			(5)
1	0.80	0.88	0.92	0.92	0.95	0.92	0.94	0.92			
3	0.96	0.97	0.96	0.98	0.96	0.94	0.97	0.98		1.03	
2	0.92 0.349	0.93 0.343	0.96 0.335	0.98 0.324	0.98 0.328	0.97 0.332	1.00 0.338	0.99 0.345		1.00 0.342	(6)
1	0.87	0.89	0.89	0.89	0.97	0.96	0.97	0.95	10°	0.93	
3								0.99			
2								0.96 0.340			(7)
1								0.85			
3								0.92		0.94	
2								0.94 0.340		0.91 0.339	(8)
1								0.88	10°	0.82	
3								0.88			
2								0.81 0.336			(9)
1								0.76			
3								0.81		0.65	
2								0.80 0.338		0.79 0.336	(10)
1								0.76	10°	0.72	
3								0.77			
2								0.73 0.335			(11)
1								0.75			

DIRECTION OF FLOW

Slope = 0.00052
n = 0.0168
Water Temp. 13°F @ 1-in depth

* Refer to Figure 2

TABLE A-6
Test Run No. 6
Five 4-in. Triangles @ 10°c.t*

(Same format as Table A-1)

December 15, 1984

DOWNSTREAM SECTIONS

Depth	15 ft		13 ft		11 ft		9 ft		7 ft		5 ft		3 ft		1 ft		FOIL SECT.	UPSTREAM 1 ft		
3															0.96					
2															0.94	0.341				(1)
1															0.90					
3															0.95			0.96 fps		
2															0.92	0.342	10°	0.92	0.352'	(2)
3															1.00					
2															0.94	0.343				(3)
1															0.86					
3															1.02			1.00		
2															1.03	0.353	10°	0.99	0.347	(4)
1															0.97			0.94		
3	1.01		1.01		1.01		1.02		1.02		1.01		1.03		1.04					
2	0.97	0.354	1.01	0.350	1.00	0.341	1.00	0.329	1.02	0.328	0.98	0.343	0.97	0.338	1.01	0.345				(5)
1	0.94		0.94		0.95		0.95		1.00		0.97		0.93		0.93					
3	0.94		1.00		1.01		1.01		1.00		1.00		1.01		0.97			1.01		
2	0.96	0.356	1.00	0.350	1.01	0.342	1.01	0.332	1.01	0.329	0.99	0.336	0.99	0.340	1.01	0.345	10°	1.00	0.348	(6)
1	0.94		0.96		0.93		0.95		0.97		1.01		1.02		0.99			0.94		
3															0.99					
2															0.98	0.345				(7)
1															0.88					
3															0.96			0.95		
2															0.96	0.344	10°	0.95	0.341	(8)
1															0.91			0.90		
3															0.92					
2															0.91	0.337				(9)
1															0.84					
3															0.86			0.90		
2															0.86	0.336	10°	0.88	0.339	(10)
1															0.85			0.83		
3															0.88					
2															0.86	0.335				(11)
1															0.79					

← DIRECTION OF FLOW

Slope : 0.000[illegible]2
n = 0.0173
Water Temp: 73 °F @ 3-in. depth

* Refer to Figure 2

TABLE A-7

Surface Water Flow Determination Parameters

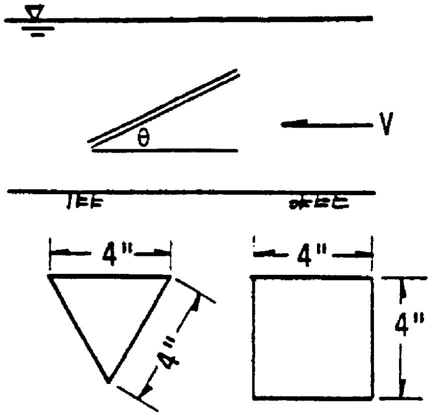
Required:

a) Drag Force, F_D

b) Manning's Roughness Coefficient, n

c) Energy Profile

d) Velocity Profile



Methodology:

a) $F_D = A_D C_D \rho \frac{V^2}{2}$

A_D (Triangle) $= \frac{1}{2} (\frac{4}{12}) \frac{2\sqrt{3}}{12} \sin\theta \; \frac{\sqrt{3}}{36} \sin\theta$

A_D (Square) $= \frac{4}{12} (\frac{4}{12}) \sin\theta = \frac{1}{9} = \sin\theta$

C_D (Triangle) = 1.5* $\qquad$ C_D (Square) = 1.5*

$\rho = 1.94 \text{ slug}/_{ft}3$ @ 73° F

b) $n = \frac{1.49}{V} R^{2/3} \; S^{1/2}$

$R = \frac{A}{P} = \frac{D(4)}{4 + 2D} = \frac{2D}{2 + D}$

c) $H = Z + \frac{V^2}{2g} + \frac{P}{\gamma}$

Set datum @ Bed, 15' downstream

$Z = 0.0052 (15 - \text{section}) + \text{Depth}$

$H = 0.0052 (15 - \text{section}) + \text{Depth} + V^2/64.4$

*Refer to Morris and Wiggert (1972)

TABLE A-8

Total Ergy Determinations Up and down stream of Positioned Plates

Test Run No. 1

Five 4-in. Squares @ 20°

Section	T.E. (ft)
-1	0.353
1	0.361
2	0.360
3	0.356
4	0.353
5	0.348
6	0.341
7	0.334

$$A_D \cdot \frac{1}{9} \sin 20° = 0.0380 \text{ ft}^2$$

$$\bar{V} = 0.92 \text{ ft/s}$$

$$F_D = 0.0380)\ (1.5)\ (1.94)\ \left(\frac{0.92^2}{2}\right)$$

$$\boxed{F_D = 0.0468 \ ^{\text{lb}}/\text{Plate}}$$

$$R_n = \frac{A}{P} = \frac{4(0.331}{4 + 2(031)} = 0.284 \text{ ft}$$

$$n = \frac{1.49}{0.92}(0.284^{1/3}\ (0.00052)^{1/2}$$

$$\boxed{n = 0.0160}$$

TABLE A-9

Total Energy Determinations Up and down stream of Positioned Plates

Test Run No. 2

Five 4-in. Triangles @ 20°

Section	T.E. (ft)
-1	0.384
1	0.382
3	0.378
5	0.361
7	0.363
9	0.365
11	0.374
13	0.381
15	0.391

$$A_D = \frac{\sqrt{3}}{36} \sin 20° \; 0.0165 \text{ ft}^2$$

$$\bar{V} = 0.89 \text{ ft/s}$$

$$F_D = (0165)\,(1.5)\,(1.94)\,\left(\frac{0.89^2}{2}\right)$$

$$\boxed{F_D = 0.0190 \,{}^{\text{lb}}/\text{plate}}$$

$$R_n = \frac{2(363)}{2\;(0.363)} = 0.307 \text{ ft}$$

$$n = \frac{1.}{0.}\,(0.307)^{2/3}\,(0.00052)^{1/2}$$

$$\boxed{n = 0.0174}$$

TABLE A-10

Total Energy Determinations Up and down stream of Positioned Plates

Test Run No. 3

Three 4-in. Squares @ 20°

Section	T.E. (ft)
-1	0.375
1	0.375
3	0.368
5	0.362
7	0.358
9	0.357
11	0.366
13	0.374
15	0.383

$A_D = 0.0380 \text{ ft}^2$

$\bar{V} = 0.87 \text{ ft/s}$

$$F_D = (0.80)\ (1.5)\ (1.94)\ \left(\frac{0.87^2}{2}\right)$$

$$\boxed{F_D = 0.0418 \ ^{\text{lb}}/_{\text{plate}}}$$

$$R_n = \frac{2(0.355)}{2 + 0.355} \quad 0.301 \text{ ft}$$

$$n = \frac{1.49}{0.82}\ (031)^{2/3}\ (0.00052)^{1/2}$$

$$\boxed{n = 0.0186}$$

TABLE A-11

Total Energy Determinations Up and down stream of Positioned Plates

Test Run No. 4

Three 4-in. Triangles @ 20°

Section	T.E. (ft)
- 1	0.375
1	0.374
3	0.365
5	0.362
7	0.357
9	0.354
11	0.364
13	0.371
15	0.379

$A_D = 0.0165 \text{ ft}^2$

$\bar{V} = 0.88 \text{ ft/s}$

$$F_D \; (0.0165)\;(1.5)\;(1.94)\;\left(\frac{0.88^2}{2}\right)$$

$$\boxed{F_D = 0.0186 \; ^{\text{lb}}/_{\text{plate}}}$$

$$R_n = \frac{2(0.355)}{2 + 0.355} = .301 \text{ ft}$$

$$n = \frac{1.49}{0.88}(0.301)^{2/3}\;(0.00052)^{1/2}$$

$$\boxed{n = 0.0174}$$

TABLE A-12

Total ergy Determinations Up and down stream of Positioned Plates

Test Run No. 5

Five 4-in. Squares @ 10°

Section	T.E. (ft)
- 1	0.362
1	0.360
3	0.359
5	0.352
7	0.346
9	0.342
11	0.360
13	0.360
15	0.365

$$A_D = \frac{1}{9} \sin 10° = 0.0193 \text{ ft}^2$$

$$\bar{V} = 0.89 \text{ ft/s}$$

$$F_D = (0.93)\ (1.5)\ (1.94)\ (\frac{0.89^2}{2})$$

$$\boxed{F_D = 0.0222\ {}^{\text{lb}}/_{\text{plate}}}$$

$$R_n = \frac{2(0.341)}{2 + 0.341} = 0.291 \text{ ft}$$

$$n = \frac{1.49}{0.89}\ (0.291)^{2/3}(0.00052)^{1/2}$$

$$\boxed{n = 0.0168}$$

TABLE A-13

Total Energy Determinations Up and down stream of Positioned Plates

Test Run No. 6

Five 4-in. Triangles @ 10°C

Section	T.E. (ft)
- 1	0.366
1	0.363
3	0.361
5	0.361
7	0.349
9	0.348
11	0.359
13	0.366
15	0.370

$$A_D = \frac{\sqrt{3}}{36} = \sin 10 = 0.0084$$

$$\bar{V} = 0.87 \text{ ft/s}$$

$$F_D\ (0.0084)\ (1.5)\ (1.94)\ \left(\frac{0.87^2}{2}\right)$$

$$\boxed{F_D = 0.0093\ {}^{\text{lb}}/_{\text{plate}}}$$

$$R_n = \frac{2(0.346)}{2 + 0.346} = .295 \text{ ft}$$

$$n\ \frac{1.49}{0.87}\ (0.295)^{2/3}\ (0.00052)^{1/2}$$

$$\boxed{n = 0.0173}$$

APPENDIX C

Microalgae Harvesting for the Hawaiian Algal Raceway System

Miroalgae Harvesting for the
Haiian Algal Raceway System

by

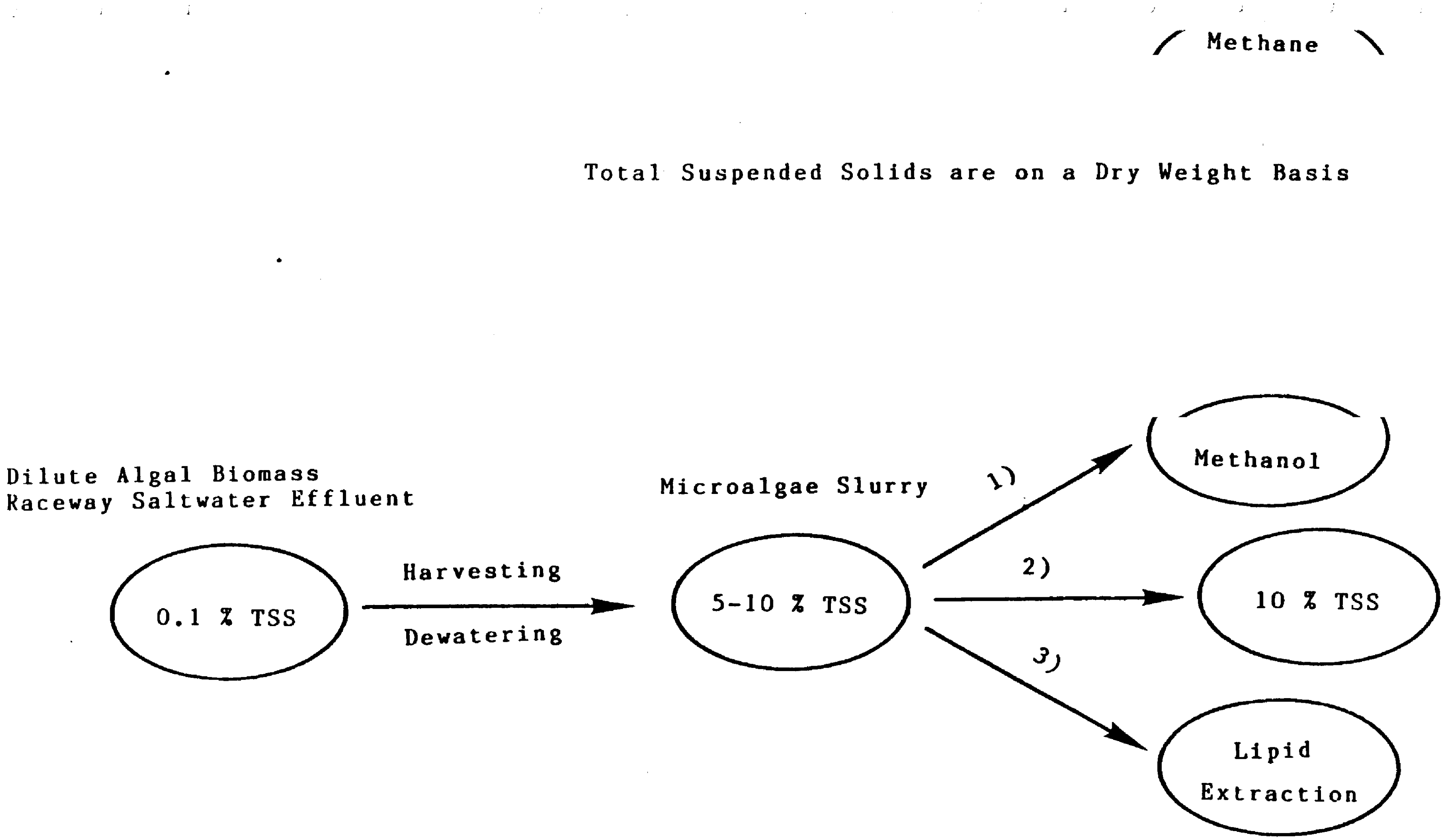
Gary L. Rogers, Ph.D.

Consulting Report

Feb. 11, 1985

Overview of Report

This report is a summary of research, review of the literature and discussions with professionals concerning techniques for harvesting microalgae. At present, there seems to be no single process of choice. In fact, few agree on microalgae ideal harvesting procedures. They do agree that the technique must be specific for a given species of algae, a particular production system, and for the expected end product. Keeping this in mind, the recommendations of this report are for the Hawaii Algal Raceway production system. The end products are 1) a slurry of 10% Total Suspended Solids (TSS), 2) a slurry of < 10% TSS that could be further processed in the production of methane or methanol, and 3) the extraction of lipid and other cellular components. Figure 1 presents an overview of the harvesting portion of this production scheme.



Total Suspended Solids are on a Dry Weight Basis

Figure 1. Harvesting Scheme for the Hawaiian Microalgae Raceway System.

Summary of Phase I research

The species of microalgae used in this study was Platymonas. The algae was produced at the Sand Island research facility. Platymonas is unicellular and approximately 15 μm in diameter. The microalgae used in this study is halophilic with an optimun salinity of 35 parts per thousand (ppt). Laws has reported productivity of 35-45 g/sq m/d at salinity of 15-30 ppt and temperature of 28-32°C. Additional information on this species of microalgae is presented in Appendix A.

Studies were conducted at the Algal Raceway research facility to determine settleability of the algae, Platymonas. An initial study utilized plastic Imhoff cones filled with a microalgae suspension from the raceways. Tests were done in the light and in the dark to determine settling characteristics of the algae and potential for harvest by sedimentation. The results were discouraging. None of the samples settled completely, even over long periods of time. The problem was likely due to the plastic material or shape of the Imhoff cones.

Another study was conducted to determine whether ultrasound sonication could be used to enhance settling and provide a means for flocculation of the microalgae. Samples of two microalgae species were sonicated for varying time periods then allowed to settle. Again, the results were disconcerting. It was shown that the control samples (not sonicated) settled at the same rate as the sonicated samples. There was essentially no difference in the settling rates.

drum test

A third study was conducted at the Algal raceway. A 55 gallon drum was used as a sedimentation basin to determine settling rates for Platymonas. In this study 80 to 90% of the cells settled out in less than one days time. Two samples of the settled algae were taken to determine the percent dry weight after settling. The results are presented in Appendix B. It was shown that the 55 gallon drum harvestor could be used to obtain effluent Total Suspended Solids (TSS) concentrations of about 7%.

crude test
And specific
To Platymonas

Microalgae Harvesting Techniques

Review of Literature

There are several procedures presented in the literature for harvesting microalgae. Tables 1, 2, and 3 list the processes that have been described. The following sections give more detail on each process with information on advantages and disadvantages as well as relative costs.

Table 1. Physical-Mechanical Processes for Harvesting Microalgae.

¢/kg; $/kg ?

Process	Final TSS	Cost	Source
Sedimentation		50	2,3,8,13,1
clarifier	.5-3%		16
thickener	?		
gravity	?		
lamella tank	1.5%		16
Centrifugation		500	3,8,13,1
rotating wall	12-22%		16
hydroclone	.4%		16
multichamber	?		
basket	?		
nozzle	2-15%		16
disc	15-25%		16
decanter	22%		16
Filtration		250-600	3,13,14
vacuum	18-37%		16
pressure	16%		16
belt	10-18%		16
cartridge	?		
deep bed	5-10%		16
ultrafiltration	<5%		16
filter basket	5%		16
Screens		50	3,8,13,14,1
vibrating	5-8%		16
rotating	?		
stationary	?		
Drying	to 30%		16
incineration	?		
sun			12
cross flow air	?		
vacuum shelf	?		
toroidal	?		
flash	?		
rotary	?		

Table 2. Chemical Processes for Harvesting Microalgae.

¢/kg?

Process	Final TSS	Cost	Source
Coagulation--Flocculation		400-450	3,12,13,15,18
Precipitation			13
Floatation		450	3,12,13,15,18
dissolved air	1-6%		16
electro	3-5%		16
dispersed air	?		
Magnetic Gradient		600	3

Table 3. Biological Processes for Harvesting Microalgae (see Making Aquatic Weeds Useful: Some Perspectives for Developing Countries, National Academy of Sciences, 1976, 175 pgs.).

Herbivorous Animals
Grass Carp
Tilapia
Silver Carp
Tawes
Silver Dollar Fish
Crayfish
Oysters
Clams
Ducks, Geese, Swans
Manatee
Water Buffalo
Capybara
Nutria

Filtration

Process Description: There are several techniques described in the literature for filtering microalgae. Included are vacuum filtration, pressure filtration, sand filtration, belt filtration, cartridge filtration, deep bed filtration, and ultrafiltration. These processes involve liquid-solid separation where the fluid is passed through a medium that retains the solids. There is a pressure drop across the medium which is required to drive the process and cause movement of the fluid through the filter.

Advantages: 1) most filters are of simple design, and 2) low maintenance costs.

Disadvantages: 1) requires a fine medium that will retain algae, 2) difficulty in handling on large scale, 3) build-up of filter cake and subsequent head loss, 4) high capital costs, and 5) inconsistent reliability.

Floatation

Process Description: Floatation involves separation by movement of the solid particle to the surface because of attached air or gas bubbles. The process reliability is dependent upon the interaction of the algae cells and the gas bubbles. Examples of the floatation process are dissolved air floatation, electrolytic floatation, and dispersed air floatation.

Advantages: 1) in the case of some algae, floatation is natural, and 2) process works for algae of any size (even used with bacteria).

Disadvantages: 1) process is quite often used in conjunction with chemical flocculation or pH adjustment, 2) reliability of process is low, 3) relative energy requirements are high, 4) both capital and maintenance costs are relatively high.

Sedimentation

Process Description: The sedimentation process is based upon movement of particles in a fluid medium by the force of gravity. Stokes Law describes the rate at which the particles descend based on the drag force on the particle, force of gravity, viscosity of the medium and size of the particle. Other factors that must be taken into account for algae settling include water turbulence, convection, temperature stratification, and wind action. Rate of settling may be increased by increasing the size of the particles. This is quite often accomplished by addition of flocculants.

Advantages: 1) little maintenance required if used without chemical additions, and 2) low energy requirements.

Disadvantages: 1) often used with polymers, and/or alum or ferric sulfate to improve separation, 2) poor reliability, and 3) long detention times required. how long

Centrifugation

Process Description: The Centrifugation process involves the movement of solid particles in the fluid by centrifugal forces. Two processes of centrifugation are the fixed wall device (hydroclone) and the moving wall device (centrifuge). In the case of the former, the liquid is fed through a nozzle tangentially against the wall of the hydroclone. The heavier particles exit through the bottom of the device and upwelling lower velocity fluid is discharged via an overflow pipe in the center. The latter process involves the rotation at high speeds to increase the rate of separation.

Advantages: 1) high reliability and high efficiency, and 2) achieve high TSS levels in final concentrate.

Disadvantages: 1) high energy requirements, 2) high capital and maintenance costs, 3) batch systems require frequent cleaning, and 4) excessive wear on equipment.

Screens and Strainers

Process Description: The microscreening process is similar to that of filtration. Straining devices of fabric, stainless steel, and polyester of fine mesh are used to separate the solids from the fluid medium.

Advantages: 1) simple design and construction, 2) ease of use, 3) relatively low capital costs, 4) low maintenance and energy costs, and 5) fairly reliable and efficient process.

Disadvantages: 1) build-up of slime on filter fabric and need for UV irradiation, 2) problems with handling fluctuations in solids levels and 3) need for periodic cleaning of the microstrainer.

Drying

Process Description: The drying process is done to reach TSS levels of above 15%. The process of dehydration may be accomplished by drying with a heated gas stream, with high velocity air movement, sun drying, and vacuum drying. Examples of these processes are: flash dryers, rotary dryers, toroidal dryers, spray dryers, vacuum dryers, and solar dehydrators.

Advantages: 1) may yield very high TSS levels, and 2) provide a stable, storable product.

Disadvantages: 1) high capital and maintenance costs, 2) may cause degradation of cellular components, and 3) high energy requirements.

Magnetic Separation

Process Description: High gradient magnetic filtration (HGMF) involves the suspension of magnetic particles in solution. The magnetite coagulates with the algae and both are separated from the solution by a magnetic field. This process is probably not feasible, especially for large facilities.

Advantages: 1) fairly reliable process.

Disadvantages: 1) not well studied, 2) high capital and maintenance costs, and 3) algae in combination with magnetite.

Biological Separation

Process Description: Fish, other vertebrates, and invertebrates have been used to remove algal populations in high density algal ponds. The technique is still largely undefined and the results are highly variable. Some of the species of aquatic animals that have been tested include; fish (*Tilapia*), other vertebrates (*Manatee*), and invertebrates (Clams and Oysters). A paper presented at the Second International Conference on Warmwater Aquaculture described the use of *Tilapia* for algal biomass recovery (Abstract presented in Appendix C).

Advantages: 1) low capital and maintenance costs, and 2) little management required.

Disadvantages: 1) interaction of biological species and respiration requirements largely unknown, 2) problems with high BOD resulting from animal fecal excretion, and 3) water quality requirements of process not well studied.

Coagulation-Flocculation

Process Description: The process of coaguation and flocculation involves the addition of lime, alum, polyelectrolytes, activated carbon, and ferric salts to aid in floc formation. The process is sensitive to pH, alkalinity, temperature, and other variables. The common "Jar Test" is used to determine suitable coagulant dosage and chemical conditions for optimum efficiency of the process.

Advantages: 1) negatively charged algae surfaces form stable flocs with some chemical flocculants.

Disadvantages: 1) process is not easily controlled, 2) require expert personnel to operate, 3) sludge cake in combination with the algae may preclude further use of the algae, and 4) difficult to recover algae.

Costs of Harvesting Processes

Tables 1, and 2 present relative costs for some of the microalgae harvesting processes. The numbers were presented by Benemann (1980) and are US dollars (1976) per million gallons. The estimated costs represent capital recovery, operation and maintenance costs.

I have also calculated capital costs for three harvesting schemes. The first harvesting process (No. 1 on Figure 1) considers methane or methanol production. An algal slurry of 3-5% TSS is achieved by sedimentation only. The process utilizes twelve 100 ft diameter settling basins, each 20 ft in depth. The basins would provide a hydraulic detention time of about 10 to 12 hours which should provide concentration to about 3-5% TSS.

The second process (Number 2 on Figure 1) considers production of an algal slurry of 10% TSS. The process train utilizes the 12 sedimention basins described earlier. In addition, 30 rotating microscreens each with a mesh opening of 10 um provide further dewatering to 10% TSS.

The last process (number 3 on Figure 1) considers the end product of purified lipid. The lipid is extracted by the supercritical carbon dioxide technique. This process train would require very expensive extraction procedures (i.e. about $5 million for a small plant of 10 tons/day according to Basta, 1984).

This data is summarized on Table 4. The total capital cost to produce 10% TSS is $3.6 million. If centrifugation were used instead of microscreens, the total capital cost would be about $25 million. Table 4 also gives a summary of physical dimensions for harvesting facilities. The expected concentration of algal slurry product is also summarized. The calculations are presented in more detail in Appendix D.

I find nothing in the literature that would suggest microscreens could be used to prepare an algal slurry of 10% TSS. The best reliable estimate would be in the range of 7 to 8% TSS (Mohn, 1980). Hence, I feel it is necessary to utilize both sedimentation and microscreening in order to reach the 10% TSS slurry.

Table 4. Summary of Costs for Microalgae Harvesting.

End Product	Final TSS	Capital Cost	Land Required
1) methane methanol ethanol	3-5%	$2.4 million	5.5 acres
2) 10% TSS	10%	$3.6 million	6.0 acres
3) lipid		> $100 million	6.0 acres

not needed for AD

what?

Summary and Conclusions

Microalgae harvesting seems to be a key limitation to the development of commercial-scale algal raceway schemes. This is due mainly to the fact that conflicting reports of harvest efficiency and harvest costs make it difficult to predict what the actual results will be in a commercial facility. Additionally, only limited work has been done on harvesting marine species of microalgae and Platymonas in particular.

Table 4 presents a summary of estimated costs and facility requirements for adaptation to the Hawaiian raceway system. It also includes estimated maintenance costs for those systems.

Recommendations

It is recommended that additional studies be conducted with the test algal species (Platymonas) on a limited scale and then pilot scale to determine the actual scale-up costs for a 1000 acre facility using the processes outlined in this study.

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APPENDICES

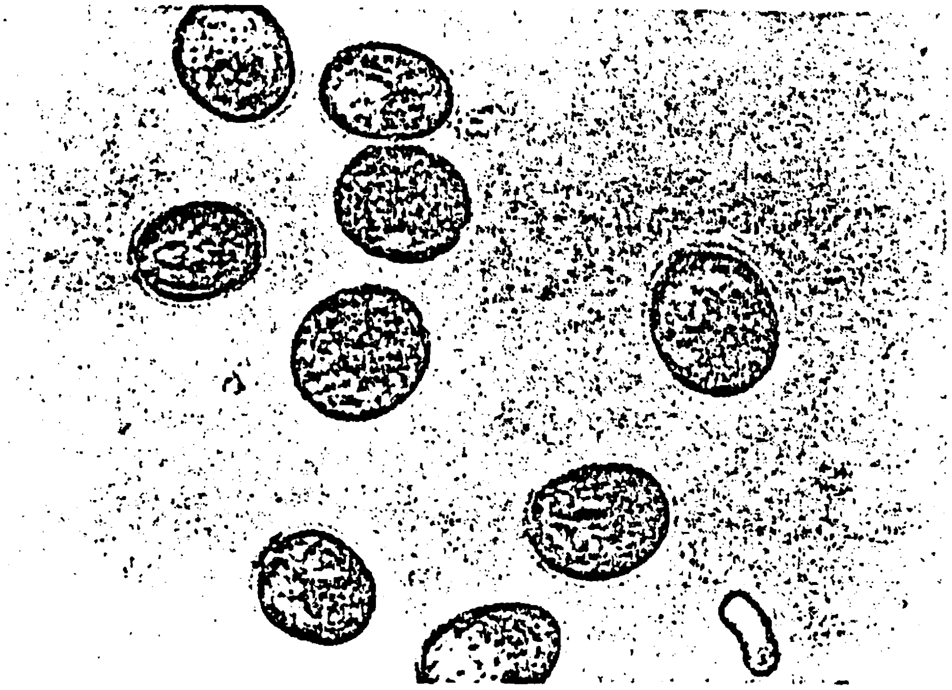
APPENDIX A

Information on <u>Platymonas</u>

Platymonas sp.

Strain: Hawaii (S/PLATY-1)

Taxonomy: Division: Chlorophyta
Class: Chlorophyceae
Order: Volvocales
Family: Tetraselmiaceae



Platymonas sp. cells. (Scale: 1 cm = 10 μm)

Collection site: Invaded raceway mass culture, Hawaii

Date: Summer 1983

Size: 13-18 μm x 13 μm

Growth form: unicellular

Growth rate at optimum (or maximum recorded): not determined

Culture conditions:

Vitamins required:	none
Available nitrogen sources:	ammonium, urea, nitrate, amino acids
Suitable media:	not determined: grown outdoors with seawater drawn from well through coral, enriched with NH_4^+(0.5-1 mM), $PO_4^{\equiv}$30.05-0.1 mM), f/2 metals (1-10X recommended concentrations), and $NaHCO_3$ (equimolar to NH_4^+).
Nutritional modes:	autotrophic
Temperature range:	not determined
optimum:	34°C (1)
Salinity range:	15 o/oo - ? o/oo (1)
optimum:	35 o/oo (1)

Chemical composition:

Growth conditions	% lipid	% protein	% carbohydrate	Ref.	Basis
SC	18	46	36	1	AFDW
SC, N(N,P)	15	24	61	1	AFDW

Lipid composition: 33% neutral lipids (1)

Fuel production options:

Option	Methane MJ/kg	Ester MJ/kg	Hydro-carbon MJ/kg	Ethanol MJ/kg	Total Recovered MJ/kg	Fraction Utilized	Liquid Fuel MJ/kg
1	16.2	0	0	0	16.2	0.685	0
2	16.2	0	0	0	16.2	0.685	0
3	10.7	4.7	2.7	0	18.0	0.761	7.4
4	12.3	0	0	3.5	15.8	0.667	3.5
5	6.7	4.7	2.7	3.5	17.6	0.743	10.9

Total energy content: 23.7 MJ/kg dry weight

Physiological note: optimum pH = 7.0 (1)

Life cycle:

Asexual reproduction by longitudinal division to form two or four daughter cells. Some species of *Platymonas* are known to form resting spores or cysts. (2)

Outdoor culture history:

1. Cultured in Hawaii raceway. High productivity (35-45 $g/m^2/day$) at a salinity of 15-30 o/oo and temp of 28-32°C. (1)

References (number available in each category):

Physiology:	49
Ecology:	17
Culture:	19
Chemical composition:	9
Taxonomy:	4
Ultrastructure:	2
Food for higher organisms:	20

Literature cited:

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APPENDIX B

Dry weights of settled algae

Table B1. Dry weights of settled algae.

Number	sample	net wt wet	net wt dry	% dry wt
1	<u>Platymonas</u>	9.50 g	3.02 g	13.5%
2	<u>Platymonas</u>	29.66 g	2.56 g	7.1%

Above assumes samples at approximately 15 ppt salinity

APPENDIX C

Abstract of *Tilapia* paper

POTENTIAL OF TILAPIA FOR TROPICAL ALGAL BIOMASS RECOVERY

John A. Colman* and Peter Edwards, Agricultural and Food Engineering Division, Asian Institute of Technology, GPO Box 2754, Bangkok 10501, Thailand.

The efficiency of algae/fish tanks in a tropical setting was investigated. Feed conversion ratios (FCR) were determined for fish cropping of algal biomass over 64 days in combined, algae/fish culture tanks. The 5 m^3 tanks were heavily fertilized with inorganic nutrients and cesspool slurry (6 g COD$\cdot m^{-2} \cdot day^{-1}$). Algal standing crop and fish growth were exceptionally high, > 70 mg dry wt$\cdot \ell^{-1}$ and > 1 g$\cdot fish^{-1} \cdot day^{-1}$, respectively. Sixty to seventy g fish (Oreochromis niloticus) were stocked in the tanks at optimal density (5$\cdot m^{-2}$), as determined by previous experimentation. Feeding rate was defined as the equivalent on a dry weight basis of added cesspool slurry and whole-tank, 24-hour net carbon production. The latter was evaluated by daily summed O_2 change in the culture tank, computed O_2 loss through the the water surface, and computed O_2 used in fish respiration. The average feeding rate was 12 g dry wt organic matter$\cdot m^{-2} \cdot day^{-1}$, more than half of which was of algal origin. Net production was less than is now commonly achieved in algal biomass culture, where an attempt is made to optimize algal productivity. FCR values were determined towards the end of the experiment during three 2-week intervals in 3 tanks and averaged 2.3 (dry wt organic matter: fresh wt fish basis). FCR values were similar to those obtained in studies using harvested dried algae as fish or livestock feed. Biomass recovery by fish cropping obviates the need for conventional algal biomass recovery involving costly concentration and drying procedures.

APPENDIX D

Calculations of harvesting process costs

Process #1 -- End product Methane or Methanol

1000 acre facility run 24 hrs/day

Total volume of water in system about 90 MG

One third of water volume daily to harvesting

Harvesting water flow rate about 30 MGD

Sedimentation basin sized according to hydraulic detention time

Assume detention time of about 10 hr.

Volume of clarifiers is 1,700,000 cubic ft

Assume clarifiers 20 ft deep and 100 ft in diameter

Require 10.6 clarifiers

Check w̄ Weissman/or collaborator

Recommendation: 12 Sedimentation basins each 20 ft deep and 100 ft diameter

Each sedimentation basin costs $200,000 for a total cost of $2,400,000

Annual operation and maintenance costs are difficult to estimate since sedimentation has not been widely tested and applied to microalgae harvesting. Based on costs provided for domestic wastewater treatment (which may or may not be directly transferable to algal harvesting), the annual O/M costs for the 30 MGD facility would be $450,000. Much of this cost is in sludge handling.

Total area required for harvesting facility is 5.5 acres uncovered

Process #2 -- End product 10% TSS

1000 acre facility run 24 hrs/day

Total volume of water in system about 90 MG

One third of water volume daily to harvesting

Harvesting water flow rate about 30 MGD

Sedimentation basin sized according to hydraulic detention time

Assume detention time of about 10 hr.

Volume of clarifiers is 1,700,000 cubic ft

Assume clarifiers 20 ft deep and 100 ft in diameter

Require 10.6 clarifiers

Recommendation: 12 Sedimentation basins each 20 ft deep and 100 ft diameter

Each sedimentation basin costs $200,000 for a total cost of $2,400,000

Also need 24 rotating microscreens on line with additional 6 microscreens for back-up

Each screen has mesh of 10 µm and handles a flow of above 15,000 gal/day

Each microscreen costs $40,000 for a total of $1,200,000 for 30 microscreens

Total cost to produce 10% TSS is $3.6 million

Physical dimension of facility is 1/4 acre covered and 5.5 acres uncovered.

Process #3 -- End product Lipid and other Cellular Components

1000 acre facility run 24 hrs/day

Total volume of water in system about 90 MG

One third of water volume daily to harvesting

Harvesting water flow rate about 30 MGD

Sedimentation basin sized according to hydraulic detention time

Assume detention time of about 10 hr.

Volume of clarifiers is 1,700,000 cubic ft

Assume clarifiers 20 ft deep and 100 ft in diameter

Require 10.6 clarifiers

Recommendation: 12 Sedimentation basins each 20 ft deep and 100 ft diameter

? excessive

Also need 24 rotating microscreens on line with additional 6 microscreens for back-up

Each screen has mesh of 10 µm and handles a flow of above 15,000 gal/day

Each microscreen costs $40,000 for a total of $1,200,000 for 30 microscreens

The cost of supercritical carbon dioxide extraction is not clear. Basta, 1984 indicates that the cost is high ($5 million for a 10 ton facility).

Total cost to produce lipid is probably near $100 million ?

Physical dimension of facility is 1/2 acre covered and 5.5 acres uncovered.

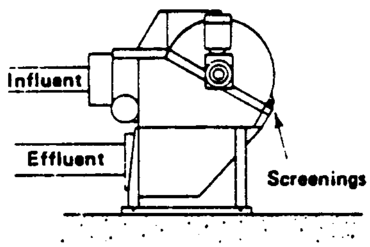
Installation Guidelines

The Rotostrainer screen can be positioned above or below ground with either a gravity or pumped influent to the headbox and a gravity discharge from the unit. The illustrations show suggested basic layouts for the influent and effluent pipework although it should be noted there are other alternative arrangements for both single and multiple units to meet specific requirements.

Screenings Handling and Disposal

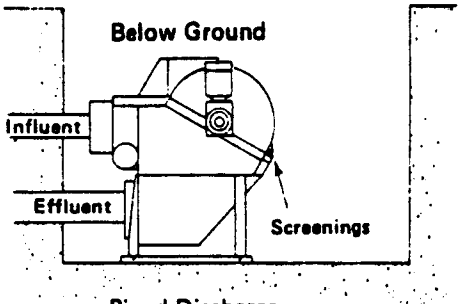
Screenings from the Rotostrainer screen are usually collected and discharged to a disposal point by a slatted trough belt or screw conveyor system. From here they may be pressed before disposal to landfill, incineration or by-product recovery depending on the type of screenings.

Above Ground



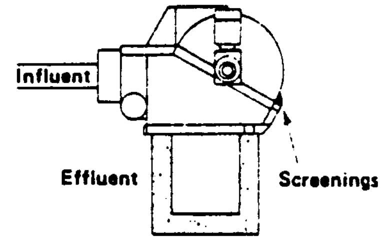
Piped Discharge

Below Ground



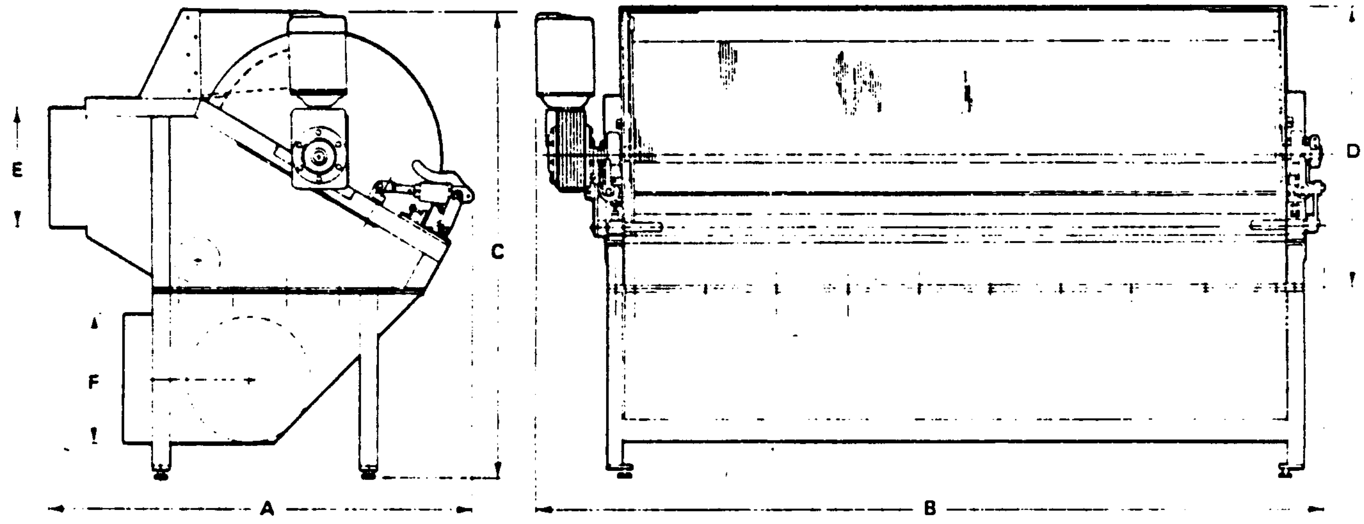
Piped Discharge

Above and Below Ground



Open Channel Discharge

Rotostrainer Dimensions



ALL DIMENSIONS IN INCHES										ALL WEIGHTS IN POUNDS			
Model No	Motor Hp.	Screen Dia.	Screen Length	Unit Depth A	Unit Length B	Unit Height W/Base C	Unit Height W/O Base D	Influent O.D. E	Effluent O.D. F	Dry Weight W/Base	Dry Weight W/O Base	Operating Weight W/Base	Operating Weight W/O Base
RSA-2512	½	25	12	45 12	29 09	45 25	30 25	4 50	8 63	300	250	500	375
RSA-2524	½	25	24	45 12	41 59	45 25	30 25	6 63	10 75	600	525	1000	750
RSA-2548	¾	25	48	50 50	66 90	51 38	30 38	10 75	14 00	750	620	1550	1100
RSA 2572	¾	25	72	50 50	90 90	51 38	30 38	12 75	16 00	900	750	2100	1450
RSA 3672	1 2	36	72	70 75	92 50	67 38	43 75	16 00	20 00	1850	1650	5450	3250
RSA-36120	1½ 3	36	120	70 75	142 44	66 75	43 75	20 00	18 00(2)	2940	2650	8450	5250

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Representative

APPENDIX D

Engineering Assumptions and Calculations

DATE:

PROJECT: MICRO ALGAE

BY: DJ

REFERENCE:

NATIONAL CONSTRUCTION ESTIMATOR (NCE)
THIRTIETH EDITION 1982
BY CRAFTSMAN BOOK CO.
CARLSBAD, CA

ALL COSTS FROM THIS REFERENCE WERE TREATED AS FOLLOWS:

MAT'L COSTS MULTIPLIED BY 1.14 TO ALLOW FOR INFLATION SINCE 1982 AND GENERALLY HIGHER COSTS IN HAWAII

LABOR COSTS MULTIPLIED BY 1.1 TO ALLOW FOR AVG. HIGHER LABOR COSTS IN HAWAII BASED ON TABLE P. 5 NCE.

CLEAR & GRUB COSTS

ASSUME:

TOTAL AREA OF FACILITY IS IN CONDITION OF A HARVESTED SUGAR CANE FIELD

FACILITY AREA = 2218 ACRES TOTAL.

REFERENCE: NCE P. 46.

CLEARING LIGHT BRUSH PER ACRE – $470.00

SUGAR CANE REFUSE IS PROBABLY LESS THAN HALF OF LIGHT BRUSH.

USE $200/ACRE.

DATE:
PROJECT: MICROALGAE
BY: DJ

SURVEYING COSTS

ASSUME:

234 RACEWAYS

2-3 MAN CREW COULD DO 3-4 RACEWAYS PER DAY

REFERENCE: NCE P. 155

$600/DAY FOR 2-3 MAN CREW.

$\frac{234}{3.5} = 66.8$ USE 70 DAYS.

OR

5 2-3 MAN CREWS FOR 14 DAYS EACH.

PROJECT: MICROALGAE
DATE:
BY: DJ

MISCELLANEOUS COSTS

ASSUME:

THE EQMT REQ'TS AND COSTS SHOWN BELOW AND ON ACCOMPANYING CALC. SHEETS

REFERENCE: AMFAC EQM'T OF HONOLULU EXCEPT WHERE NOTED

			TOTAL ALL
2	HYDRAULIC CRANES (USED)	80,000 EA	= $ 160,000
4	FOUR TON FORKLIFTS	20,000 EA	$ 80,000
20	UTILITY VEHICLES (GOLFCARTS)	8,500 EA	$ 170,000
5	LT TRUCKS (PERSONAL EST.)	10,000 EA	$ 50,000
4	HEAVY TRUCKS (PERSONAL EST.)	25000 EA	$ 100,000
2	FLAT BED TRUCKS (PERSONAL EST)	50,000 EA	$ 100,000
5	HYROFOIL PUMPS (M & W PUMP) (PORTABLE, HYDRAULIC DRIVE FOR EMERGENCY PUMP REPLACEMENT)	50,000	$ 250,000
15	CLN MACHINES (PERSONAL EST) (SEE ATTACHMENTS)	41667	$ 625,005
7	VACUUM HARV. SWPERS (PERSONAL EST) (SEE ATTACHMENTS)	35,000	$ 245,000

DATE:

PROJECT: MICROALGAE

BY: DJ

VACUUM PUMP SWEEPER MACHINES TO P/U SETTLED ALGAE.

\# OF VEHICLES REQUIRED

ASSUME

1. EACH VEHICLE HAS TANK TO HOLD 28 M^3 OF WATER (8' x 20' CYL. TANK)
2. 10% SOLIDS CONCENTRATION AFTER DRAINING POND 1500 M^3 OF ALGAL SLURRY PER POND

CALCULATIONS:

$$\frac{1500\,m^3}{28\,m^3} = 54 \text{ TRIPS}$$

USE 6 VEHICLES ⟶ 9 TRIPS EACH PER 8 HR. SHIFT

IF VEHICLES CAN SWEEP 5 M WIDE SWATH AND 4 HRS OF 8 HRS IS SWEEPING + 4 HRS IN TRANSIT

$$\frac{286\,m \text{ WIDE POND}}{5\,m \text{ SWATH}} = 57.2 \text{ 5 M SWATHS.}$$

≃ 10 SWATHS FOR EACH OF 6 VEHICLES

$$\frac{256\,m \times 10 \text{ SWATHS}}{4 \text{ HRS}} = 0.44 \text{ mph}$$

REASONABLE SUCTION SPD!

MAKAI OCEAN ENGINEERING, INC.
P O BOX 1206, KAILUA, OAHU, HAWAII 96734
(808) 259-5940

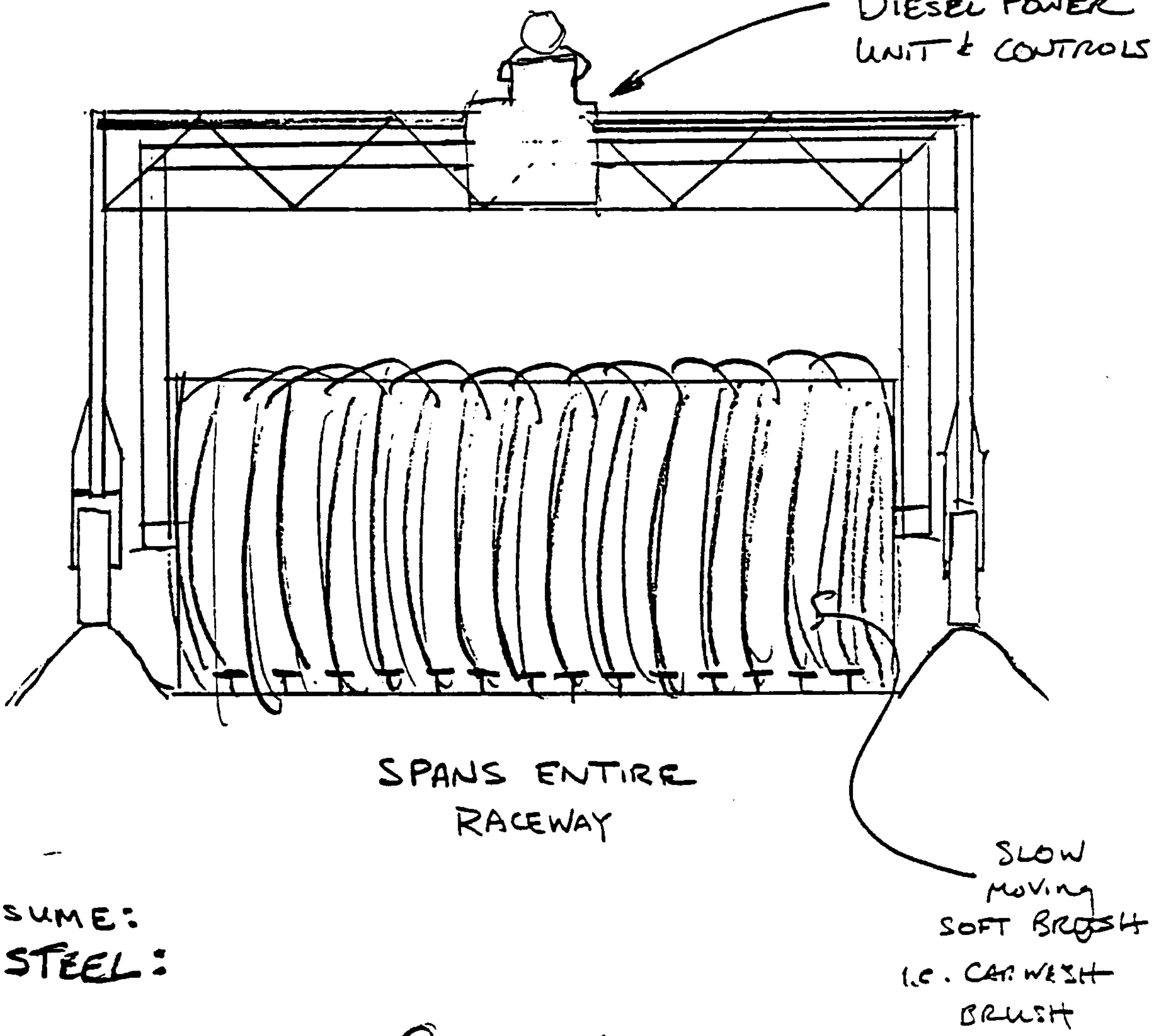
520

DATE: 2/9

PROJECT: MICROALGAE

BY: DJ

CLEANING MACHINE ESTIMATES



ASSUME:

STEEL:

4 TRUSSES EA @ 1 TON = 4 TONS
DRIVE TRAIN DIESEL = 1 TON
OTHER STRUCTURAL STEEL = 2 TONS

REFERENCE:

	MAT'L	LABOR	
NCE HEAVY STEEL WELDED = PER lb	0.70	0.08	= 0.78/lb

6000 × 0.78 = $4240
ENGINE + TRANSMISSION = 15000
OTHER — = 15000
~ 35,000

ENGINEERING DEVELOPMENT = $100,000

PROJECT: MICROALGAE
DATE:
BY: DJ

CLEANING MACHINE — NUMBER REQ'D?

TRAVEL SPEED ≅ 2 MPH $(0.89 \frac{m}{sec})$

IN 24 HRS TOTAL TRAVEL = 77268 M

44 RACEWAYS/DAY

5.3 MACHINES REQ'D FOR FACILITY IF CLEANING IS TO BE CARRIED OUT IN ONE DAY.

USE 7 MACHINES × 35,000 + 100,000 = 49,300/EACH

IF MACHINES ARE USED ONLY 12 HRS/DAY

ASSUME 15 MACHINES × 35000
\+ 100,000
$41,667/EACH.

DATE:
PROJECT: MICROALGAE
BY: DJ

SETTLING POND COSTS

ASSUME:
- SEE ATTACHED CALCULATIONS
- 2 M DEPTH, 2.5 M BERMS (2:1 SLOPE)
- POND HOLDS 1/3 OF FACILITY WATER VOLUME – 163,588 m^3
- SOIL CEMENT LINING 6" THK.
- 286 M × 286 m
- BOTTOM OF POND IS EXCAVATED 24.5 cm DEEP = 20,040 m^3 DIRT + 10% FOR BOTTOM PIPE CHANNELS & SUMP = 22044 m^3 (28878 CY)

REFERENCE:

EXCAVATION NCE P167
FOR 6" LIFTS – \$2.65/CY ADD \$1/CY SINCE LIFTS ARE HIGHER THAN 6"

\$3.65/CY

TOTAL ALL
\$105,405

LINER
6" SOIL-CEMENT AREA = 82682 m^2 (883071 SF)
TOTAL SOIL TREATED = $\frac{441535}{0.97}$ CF = 455191 ft^3

6" SOIL CEMENT (LIME) IS 50% INCREASE OVER 4" SOIL CEMENT (SEE RACEWAY LINER COST)

MATL	LABOR	TOTAL	TOTAL ALL
0.14/SF	0.14/SF	\$0.28/SF	\$247,260

PUMPS 3 PUMPS PER SETTLING POND
15000 GPM EA. 15' HD – 55 HP REQ'D
INSTALLED COST – 25,000 (PERSONAL EST)

TOTAL ALL
75,000

MAKAI OCEAN ENGINEERING, INC.
P O BOX 1206, KAILUA, OAHU, HAWAII 96734
(808) 259-5940

DATE:

PROJECT: MICROALGAE

BY: DJ

PIPE 20"Ø PVC 100 psi, 9 x 300 m = 2700 m (8856')
(APACHE PLACTICS & NCE)

MATL	INSTL	TOTAL		TOTAL ALL
20.56	8.0	28.56	=	$ 252927

VALVES (MANUAL) 9 @ 2300 EA INSTL. FRESNO VALVE.

TOTAL ALL
$ 20700

CONCRETE. PUMPING SUMP = 3 x COST OF RACEWAY PUMP SUMP (PERSONAL EST)
NCE P186

3 x 15 CY = 45 CY @ 235/CY

TOTAL ALL
$ 10575

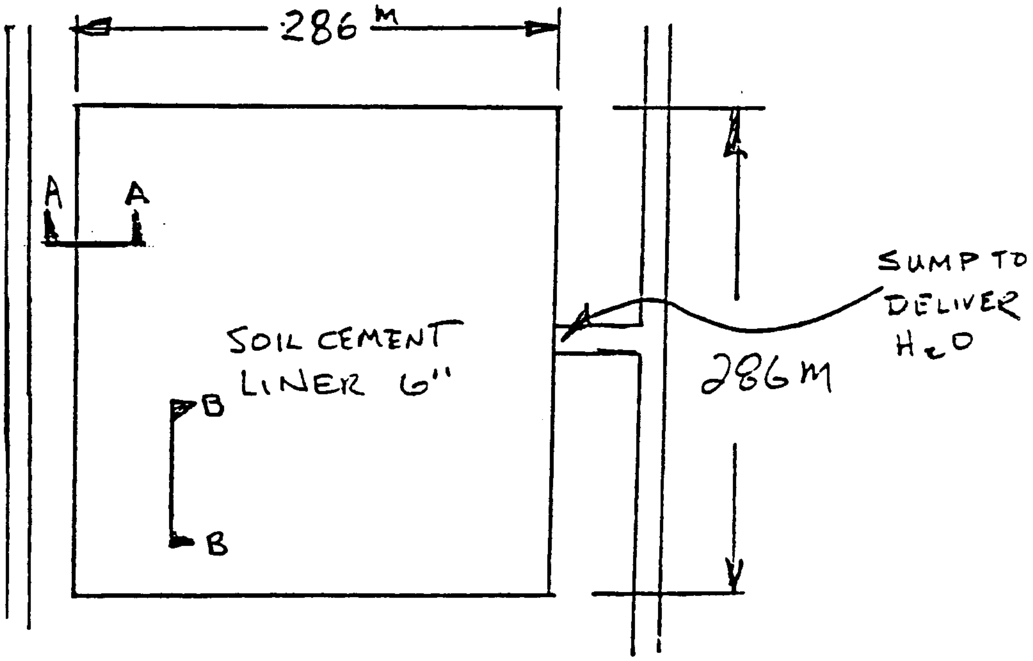
PROJECT: MICROALGAE
DATE:
BY:

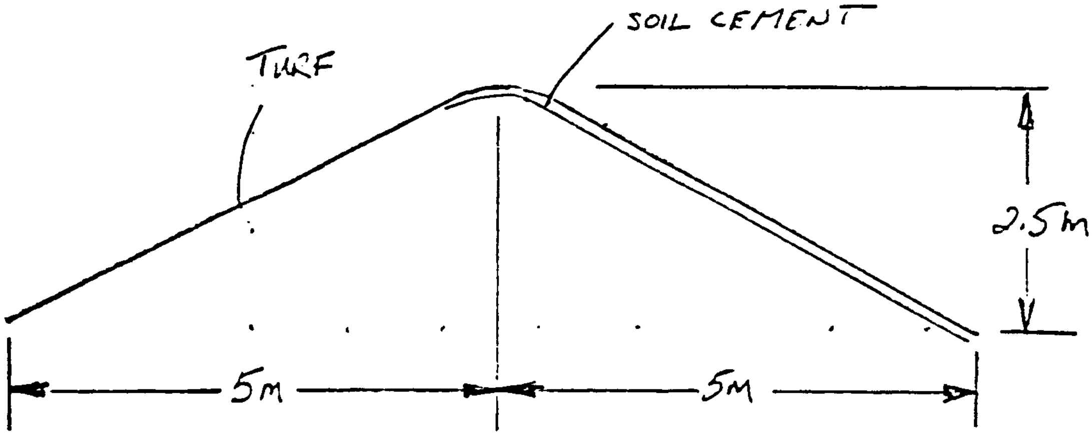
SETTLING POND CALCULATIONS

4 PONDS REQ'D

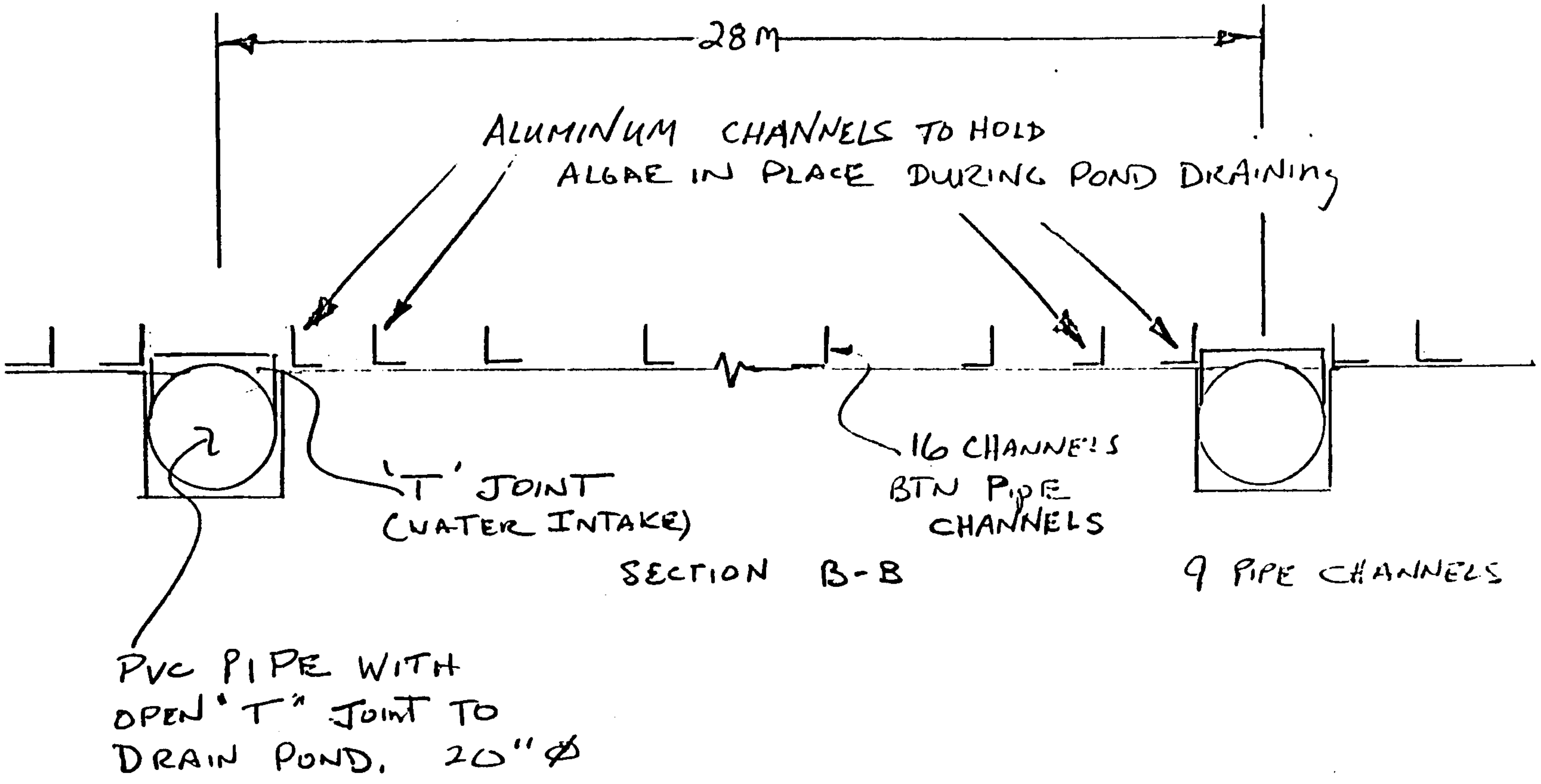
EVERY DAY - 163,588 m^3 OF WATER IS PROCESSED.

TO HOLD THIS WATER - SETTLING POND 2 m Deep. with square shape: SIDES 286 m Long





SECTION A-A



SECTION B-B

IF EACH PIPE (9 TOTAL) FLOW AT AVG 15000 GPM POND WILL EMPTY IN 5.3 HRS. HD LOSS/100FT @ 15000GPM 20"Ø ≅ 2.5 ft.

DATE:

PROJECT: MICROALGAE

BY: DJ

LINER COST

ASSUME.

3% LIME BY WEIGHT REQ'D
4" LAYER OF SOIL CEMENT
232435 ft² PER RACEWAY, 875m AVG LENGTH.
138 TONS/LIME PER RCWAY (SEE ATTACHED CALCULATION)

REFERENCE.

QUICKLIME COST (CALIFORNIA PORTLAND CEMENT CORP.)
$3.47/60lb = 115.67/TON

SHIPPING TO LA
$150/25TON = $6/TON

SHIPPING TO HONO
MATSON RATE. 3.78/100lb = 75.6 TON (HIGH!)
ASSUME PRIVATE DRY BARGE COULD DO SHIPPING FOR 1/2 MATSON RATE (PERSONAL EST.)
SHIPPING TO HONO = 40/TON

TOTAL PER TON MAT'L = $146 FOB HONO.
138 TONS PER RCWAY = 0.09/SF

INSTALLATION
(REF: DICK DEGRAFFENRIED) 0.09/SF.
SOIL STABILIZATION
IMPERIAL CTY CALIF.

DATE:
PROJECT: MICROALGAE
BY: DJ

LIME REQ'D

212,460 ft² for 811 m LONG RACEWAY
(SEE EARLIER CALC.)

FOR 844 m Raceway EACH ONE

$$\text{IS} \quad \frac{256\,(212{,}460)}{234} = \underline{\underline{232{,}435 \text{ ft}^2}}$$

ASSUME Soil Density = 115 $\frac{lb}{ft^2}$ (REF.: MARK'S ME. MANUAL)

FOR 4" DEPTH

$$\text{TOTAL WT (SOIL + LIME)} = \frac{\frac{4}{12} \times 232{,}435 \times 115 \frac{lb}{ft^3}}{0.97}$$

3% of TOTAL WT IS LIME

= 9,185,575 lbs

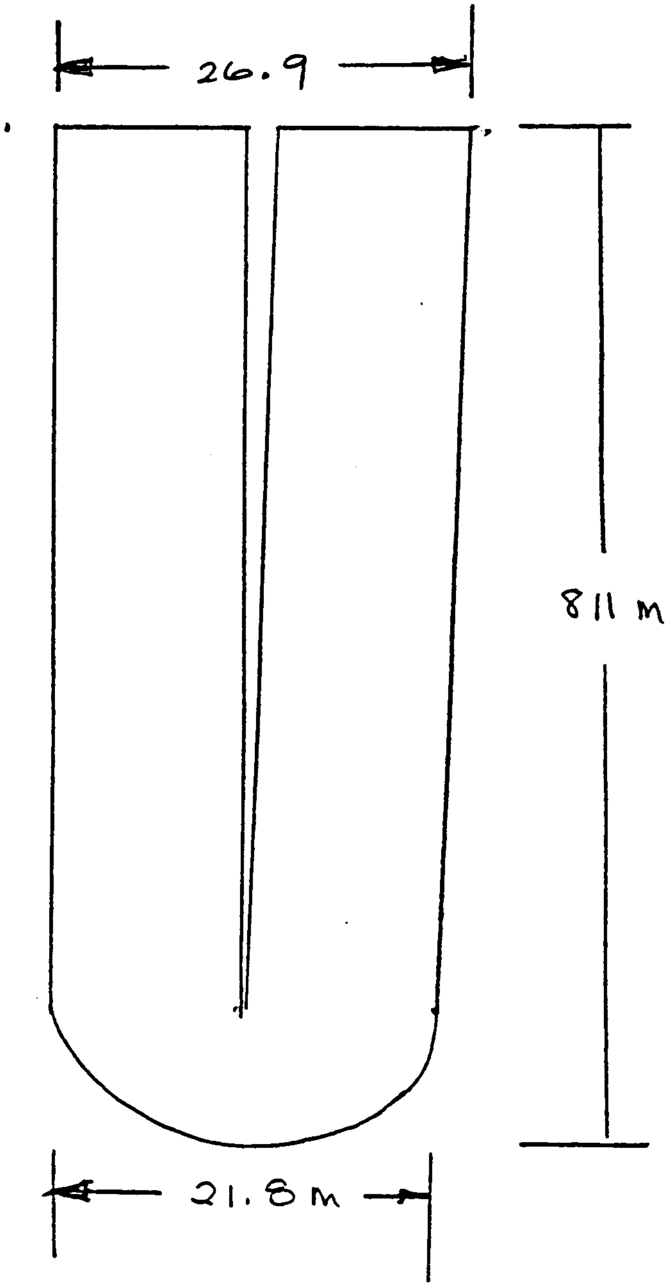
= 4593 Short TONS

LIME WT/RACEWAY (243 RACEWAYS) = $\underline{\text{138 TONS}}$

COST PER Sq FT (MATL = $\overset{\$}{0.09}$/sq ft

INSTALLATION = 0.09 sq ft.

SLOPED POND LINER AREA



$$\frac{21.8 + 26.9}{2} \times 811 = 19748\ m^2 \quad (212460\ ft^2)$$

HOLD TOTAL AREA UNDER WATER CONSTANT, THEN FOR OTHER LENGTH RACEWAY – N = # OF RCWYS

$$AREA = \frac{212460 \times 256\ \text{RACEWAYS}}{N}$$

DATE:

PROJECT: MICROALGAE

BY: DJ

FOIL COST.

ASSUME:

- DESIGN AS SHOWN ON ATTACHED PAGE
- CLEAN MACHINE WILL EXERT 10 lb LOAD ON FOIL PLATE IN HORIZ. DIRECTION.
- ALUM. 5086 CONSTRUCTION.

REFERENCE: DUCOMMIN METAL (HONO)

1/4" ∅ ALUM ROD 0.87 FT REQ'D/FOIL

COST $.13/FOIL

1/8" FLAT SHEET 4'x12' SHEET (432 4"x4" PLATES)
COST OF SHEET = $178
COST PER 4"x4" PLATE = $0.41/PLATE

\- FOILS -
MAT'LS - $.53 ADD 10% FOR GROUT ETC
= $0.60

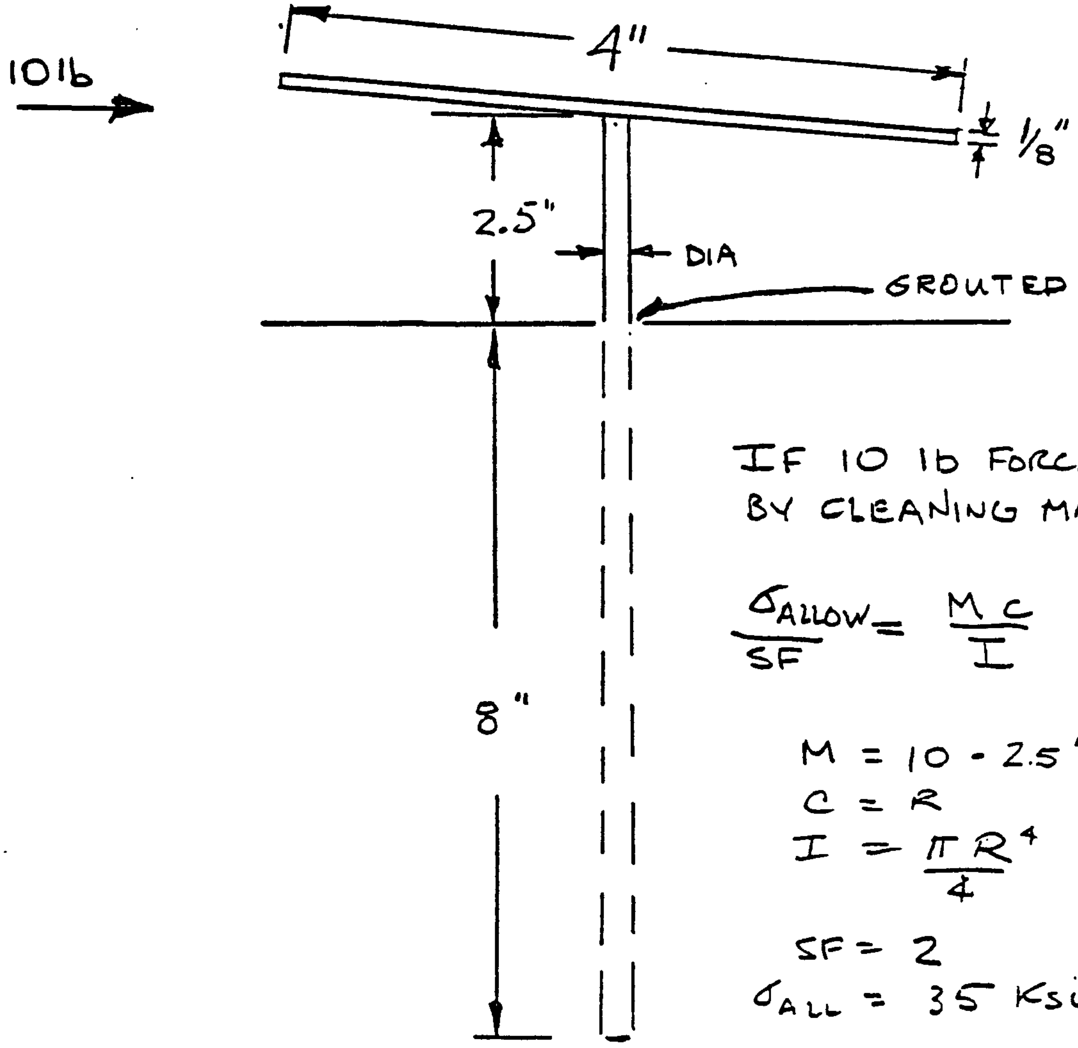
ASSEMBLY CUT & WELD (PERSONAL EST) = $1.00

INSTALL (30/HR @ $15/HR) = $.50

COST PER INSTALLED FOIL $2.10

PROJECT: MICROALGAE
DATE:
BY: DJ

FOIL DESIGN CALCULATION



IF 10 lb FORCE APPLIED BY CLEANING MACHINE

$$\frac{\sigma_{ALLOW}}{SF} = \frac{M\,c}{I}$$

$M = 10 \cdot 2.5'' = 25 \text{ in} \cdot \text{lb}$

$c = R$

$I = \frac{\pi R^4}{4}$

$SF = 2$

$\sigma_{ALL} = 35 \text{ ksi (ALUM)}$

$$R = \left(\frac{M \cdot SF}{\frac{\pi}{4} \cdot \sigma_{ALL}} \right)^{1/3}$$

$R = 0.122 \text{ in}$

$D = \underline{\underline{0.25 \text{ in}}}$ 1/4" ROD

REQ'D FOR CONSTRUCTION

20cm ON CENTER W.R.T. WIDTH
3 m ON CENTER WRT RUNNING L.
∴ 26117 in 1600 m RACEWAY

MATL	1/4" ALUM (5086) ROD	– 0.87 ft/FOIL
	4"×4" PLATE (5086)	– 0.111 SF/FOIL

DATE:

PROJECT: MICROALGAE

BY: DJ

HARVEST SYSTEM WATER CHANNEL COSTS

ASSUME:

- CONCRETE CHANNELS OF VARYING WIDTHS CARRY HARVEST WATER
- RECTANGULAR CROSS-SECTION CHANNEL WITH WATER DEPTH = 1/2 WIDTH
- REINFORCED CONCRETE - 4" THK.
- WIDTH OF CHANNEL REGULATED BY AVAIL. SLOPE OF LAND.
- SEE ATTACHED CALCULATIONS.

REFERENCE: NCE

EXCAVATION - 24 460 CY
$ 4.5/CY

PAGE 166
TOTAL ALL
110070

REINFORCED CONCRETE - 4160 CY
$ 235/CY

PAGE 186
TOTAL ALL
977,600

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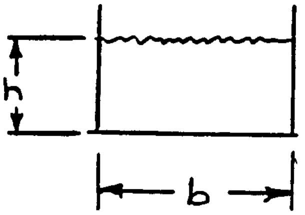
PROJECT: MICROALGAE
DATE:
BY: DJ

HARVEST SYSTEM WATER TRANSPORT

HEAD LOSSES IN PIPING SYSTEM WILL BE TOO GREAT TO HAVE GRAVITY FEED SYST.

OPEN CHANNEL FLOW CALC.'S



OPTIMUM DIMENSIONS FOR RECT. CHANNEL CROSS-SECTION

$$h = \frac{b}{2}$$

$$v = \frac{1.49}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$

REF:

$$R = \frac{A}{P} \qquad A = \frac{b^2}{2} (m^2)$$

$$P = 2b (m)$$

$$S = \frac{HDLOSS}{LENGTH}$$

v = VEL (m/sec)

$n = 0.013\ m^{1/6}$ (CONCRETE)

$$S = \left[v \frac{0.013}{1.49} \left(\frac{b}{4}\right)^{-2/3} \right]^2$$

GPM	b	v	S	
5000	2'	1.70	$2.7(10^{-3})$	←
15000	5'	0.82	$1.83(10^{-4})$	
15000	4'	1.27	$6.02(10^{-4})$	
15000	3'	2.26	$2.79(10^{-3})$	
10000	3'	1.51	$1.24(10^{-3})$	←
15000	3.5'	1.66	$1.23(10^{-3})$	←
5000	3'	0.75	$3.1(10^{-4})$	←
10000	4'	0.85	$2.67(10^{-4})$	←
25000	6.5'	1.13	$2.46(10^{-4})$	←

REQ'D CHANNELS

1. 1400' of 2' CHANNEL (CAP = 5000 GPM) SLOPE = 0.27%
2. 5000' " 3.5' " (" = 15000 GPM) Slope = 0.123%
3. 7000' " 3.0' " (" = 10000 GPM) Slope = 0.124%
4. 1400' " 3' " (" = 5000 GPM) Slope = 0.031%
5. 6200' " 3' " (" = 5000 GPM) " = 0.031%

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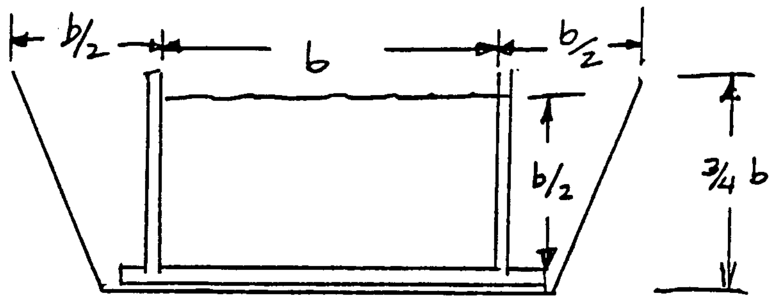
PROJECT: MICROALGAE
DATE:
BY: DJ

5' 6. 7400' of 4' CHANNEL (CAP. = 10000 GPM), SLOPE = 0.027%
2' 7. 6400' " 6.5' " (" 35000 GPM) " = 0.024%

EXCAVATION REQ'D.



REQ'D EXCAVATION $= \left[b \times \frac{3}{4} b + \frac{b}{2} \times \frac{3}{4} b \right] \times L$

$= \left[\frac{3}{4} b^2 + \frac{3}{8} b^2 \right] L = \underline{\underline{\frac{9}{8} b^2 L}}$

REQ'D EXCAVATIONS (#'s correspond to those above)

1. 6300 cu ft (.233 CY)
2. 68906 cu ft (2552 CY)
3. 70,875 " " (2625 CY)
4. 14175 " " (525 CY)
5. 62775 " " (2325 CY)
6. 133200 " " (4933 CY)
7. 304200 " " (11267 CY)

24,460 CY EXCAVATED

CONCRETE REQ'D:

$= \left[b \cdot \frac{4}{12} + 2\left(\cancel{\frac{3}{4}}\right) b \cdot \frac{\cancel{4}}{12} \right] L = \frac{5}{6} b L$

1. 2324 cu ft (86.0 CY)
2. 14525 " " (538 CY)
3. 17430 (646 CY)

DATE:

PROJECT: MICROALGAE

BY: DJ

CONCRETE CONT.

4.	3486	CF	(129 CY)
5,	15438	CF	(572 CY)
6.	24568	CF	(960 CY)
7.	34528	CF	(1279 CY)
			$\boxed{4160 \text{ CY}}$

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PROJECT: MICROALGAE
DATE:
BY: DJ

PIPE COSTS ASSOCIATED RACEWAY BRANCH LINE:

ASSUME: SEE ATTACHED SKETCHES

PIPE REFERENCE: APACHE PLASTICS
CALIFORNIA.
&
EXTROPOLATION FROM NCE P. 172

PIPE COSTS:

16" ⌀ PVC 100 PSI – 177' REQ'D

MAT'L	INSTL	TOTAL	TOTAL ALL
13.56/LF	5.56/LF	19.12	$ 3384.24

2" ⌀ PVC 100 PSI – 65.6' REQ'D

MAT'L	INSTL		TOTAL	TOTAL ALL
$ 0.70/LF	2.00/LF	–	2.70/LF	$ 177.12

TRENCHING NCE P 166

88.7 CY TO BE REMOVED @ 4.50/CY

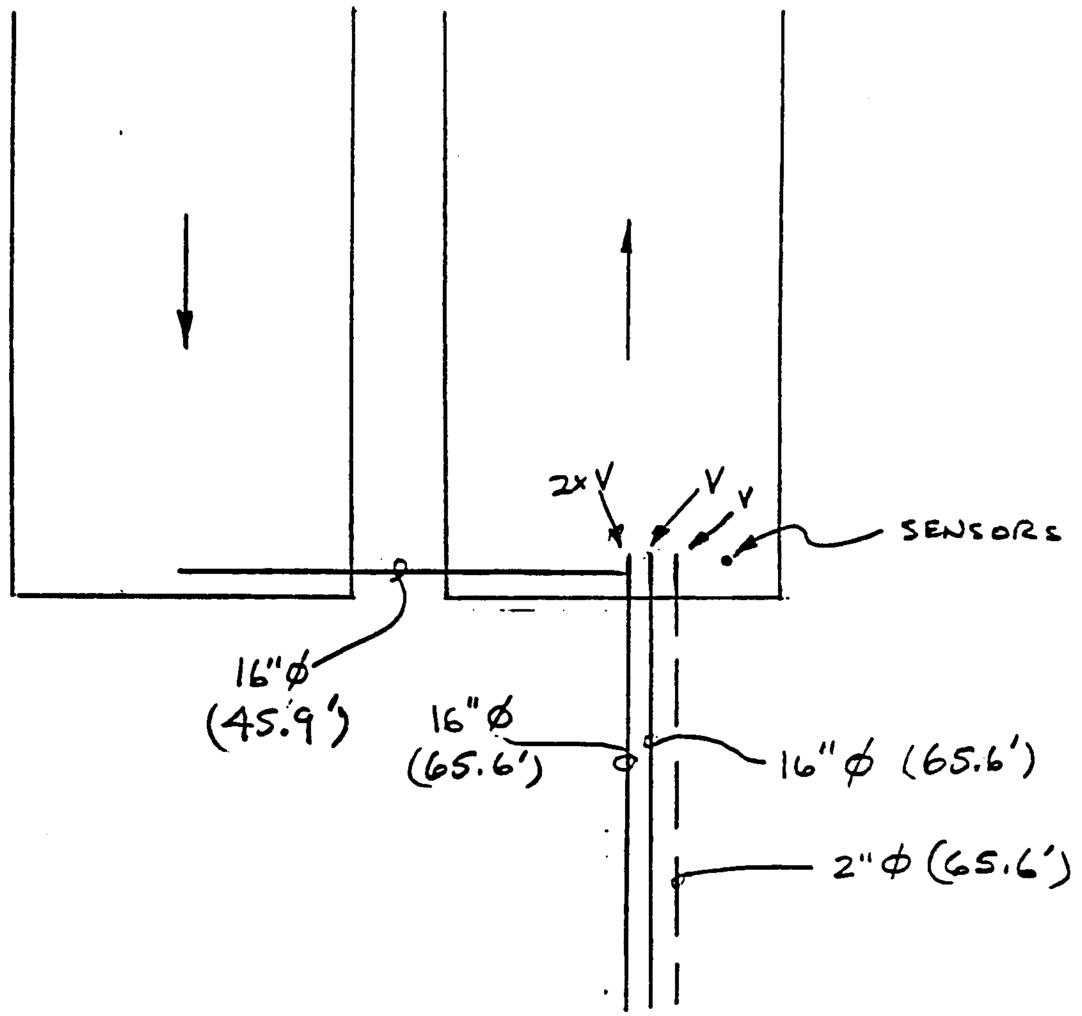
TOTAL ALL
$ 399.15

VALVES REF: FRESNO VALVE

MANUAL GATE VALVES INSTALLED — TOTAL ALL
16" ⌀ – $ 2300 × 3 = $ 6900
REMOTE CONTROL → 2" ⌀ – $ 60

SENSORS – pH, FLUID LEVEL INDICATOR, TEMP

PROJECT: MICROALGAE
DATE:
BY: DJ

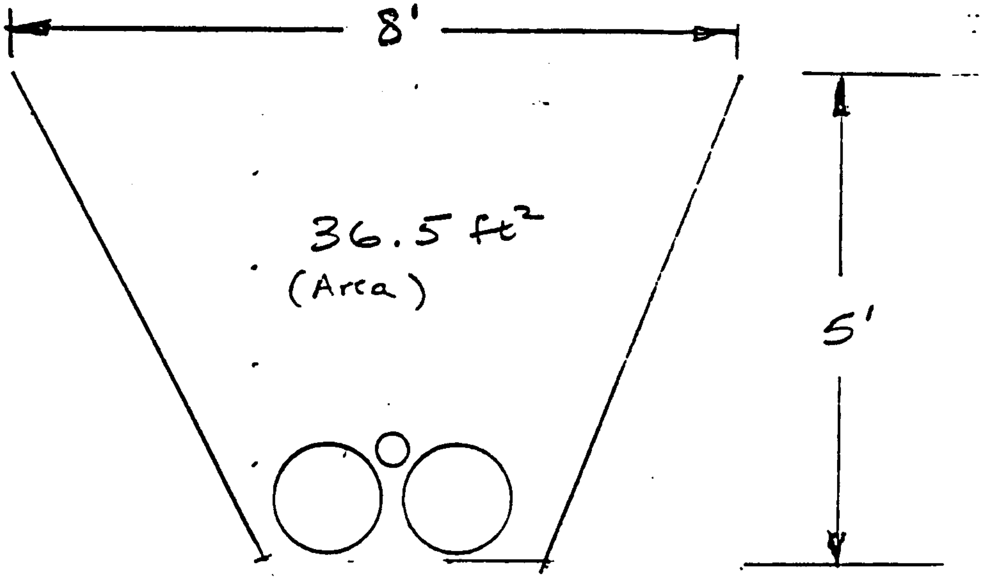


DATE:
PROJECT: MICROALGAE
BY: DJ

TRENCHING FOR PIPES
TO RACEWAY SUMP END

TRENCHING W/ BACKHOE P 166 NCE

		MAT'L	LABOR
FOUNDATION WALLS			
MOST JOBS		1.75	2.75 =
18" TO 48" TO 7' DEEP	=	4.50 /CY	



FOR 20 M TRENCH — 88.7 CY MUST BE REMOVED

DATE:

PROJECT: MICROALGAE

BY: DJ

CALCULATION OF AREAS

CO$_2$ STORAGE:

$616' \times 6' \times \frac{1}{90} = 4106$ sq ft/DAY

90 ← 10% PACKING FACTOR

(0.038 HA/DAY)

NUTRIENT STORAGE

ASSUME 60ft^2 PER 12' × 4' TANK,

3 MONTH SUPPLY @ 10TANK/DAY = 54,000 sq FT

+ 1 MONTH STORAGE = 17000 sq FT

91000 sq FT (0.71 HA)

HARV AREA (SETTLING PONDS)

$(286 + 10 + 10)^2 / 10000 = 37.5$ HA

+ 20% = 50 HA.

BLDG AREA.

OFFICES (4000 sq FT) + 500% FOR GRDS

= 12000 SQ FT (0.11 HA)

WAREHSE + SHOPS + LAB (20,000 sq FT) + 200% FOR GRDS

= 60,000 SQ FT (0.54 HA)

EMPLOYEE SPACE (8000 sq FT) + 500% GRDS

= 48000 SQ FT (0.45 HA)

BUILDING AREA TOTAL = 1.1 HA

PROJECT: MICROALGAE

DATE:

BY: DJ

EFFLUENT AREA

10' WIDE TRENCH 7600' LONG

= 76000 SF
(0.71 HA)

FEEDER RD AREA

11400 FT OF 40 M WIDE ROAD = 13.9 HA

22800 FT OF 20 M WIDE ROAD = 13.9 HA

PIPE CORRIDOR OCCUPIES 5 M OF ROADWAY.

TOTAL = 27.9 HA

PROJECT: MICROALGAE

DATE:

BY: DJ

MAINTENANCE ASSUMPTIONS

RACEWAYS

3% OF INITIAL COST MUST BE SPENT PER YR (PERSONAL EST.)

10% OF INITIAL COST MUST BE SPENT PER 5 YRS (PERSONAL EST.)

ROADS

5% OF INITIAL COST PER YR ON FEEDER ROADS (PERS. EST)

EVER 5 YRS RACEWAY ROADS ARE REGRADED, (PERS EST)

BLDGS

1% OF BLDG INITIAL COST PER YR (PERS. EST)

MOVING EQMT

3% OF INITIAL COST PER YEAR (PERS. EST)

REPLACE ALL EQMT EVERY 8 YEAR (PERS. EST)

PUMPS + VALVES.

$100 PER PUMP (253 LGE WATER PUMPS) PER YR (BASED ON CONVERSATIONS WITH M & W PUMP)

$1000 FOR PUMP REBUILD EVERY 5 YRS (M & W PUMP)

DATE:

PROJECT: MICROALGAE

BY: DJ

PIPES

2% PER YR ON PIPES FOR 1ST 10 YRS (PERS. EST)

4% PER YR ON PIPES FOR LAST 15 YRS (PERS EST)

HARVEST SYSTEM.

3% PER YR OF INITIAL EXCAVATION & LINER COST (PERS EST)

10% OF INITIAL EXCAVATION & LINER COST EVERY 5 YRS (PERS EST)

CHANNELS

1% PER YR OF INITIAL EFFLUENT AND HARVESTOR CHANNEL COST. (PERS EST)

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DATE:

PROJECT: MICROALGAE

BY: DJ

CO₂ DELIVERY SYSTEM COSTS

ASSUME:

- 1639 lbm (14604 SCFM) 12 HRS/DAY CO_2 SEE ATTACHED CALCS. FOR UNDERLYING ASSUMPTIONS.
- 14" Ø PIPE IS ADEQUATE, W/10 psig BLOWERS AT SOURCE.
- LENGTH OF PIPE = 25540' TO FACILITY
- ANOTHER 29000' REQ'D FOR SITE DIST.
- VALVE EVERY 1/2 MILE = 21 TOTAL

REFERENCE:

PIPE COST APACHE PLASTICS CALIFORNIA.
14" Ø PVC 100 psi 54540' TOTAL REQ'D

MATL	INSTL (NCE 172)	TOTAL
11.33/LF	5.00/LF	= 16.33

TOTAL ALL
\$ 890635

VALVES FRESNO VALVE
21 REQ'D \$ 2300 INSTALLED

TOTAL ALL
\$ 48300

BLOWERS ARVAY MACHINERY (HONOLULU)
17 REQ'D SUNDSTRAND D32-30
1000 SCFM @ 10 PSIG 75 HP \$ 9900 EACH

TOTAL ALL
168,300

BLOWER CONTINUOUS LOAD
50 HP (37.3 KW)
12 HR/DAY 365 DAY/YR

TOTAL ALL
2,776,241 KWH/YR

DATE:
PROJECT: MICROALGAE
BY: DJ

CO2 REQUIREMENT

Assumptions

1. Production — 50 gm/m². day AFDW
2. 50% OF AFDW IS INORGANIC CARBON
3. 70% uptake EFFICIENCY OF CO_2 DIFFUSERS.
4. 256 - 1600 m x 10 RACEWAYS MAKE UP FACILITY
5. CO_2 supplied 12 HRS/DAY ONLY.

CALCULATION:

$$\frac{50\ \text{gm}}{\text{m}^2 \cdot \text{day}} \times \frac{0.5\ \text{gm C}}{\text{gm ALGAE}} \times 16{,}000\ \text{m}^2 \times 256\ \text{RACEWAYS}$$

$$\times \frac{44\ \text{gm}\ CO_2}{12\ \text{gm C}} \times \frac{\text{Kg}\ CO_2}{1000\ \text{gm}\ CO_2} \times \frac{1}{0.7\ \text{eff}} \times \frac{1\ \text{day}}{12\ \text{HRS}} =$$

$$= 44698\ \frac{\text{Kg}\ CO_2}{\text{HR}} \quad \left(\begin{array}{l} 14604\ \text{SCFM} \\ 1639\ \text{lbm/min} \end{array} \right)$$

$$\rho_{CO_2\,\text{STD}} = 1.84\ \frac{\text{Kg}}{\text{m}^3}$$

BASED ON DARCY-WEISBACH FORMULA.

```
20    ! "GASHDL"  WILL CALCULATE THE HEAD LOSS IN A CO2 PIPELINE
21    Avg$="N"
40    INPUT "GAS PRESSURE AT PIPE HEAD, PSIA",P1
60    INPUT "GAS TEMPERATURE AT PIPE HEAD, DEG F",T1
80    INPUT "MAXIMUM CO2 FLOW, LBS/MIN",Mflow
100   INPUT "PIPE INSIDE DIAMETER, INCHES",D
120   INPUT "LENGTH OF PIPE, FT",L
140   Ro=P1*144/35.11/(460+T1)      ! R-CO2 = 35.11
160   Cfm=Mflow/Ro
180   Vel=Cfm/(D/12)^2/(PI/4)/60            ! FT/SEC
200   Mu=.0267*.000672         ! .0267 centipoise @ 120 DEG F
220   Re=Vel*D/12*Ro/Mu
240   PRINT LIN(2)
260   PRINT USING "D.DE";Re
280   INPUT "FIND FRICTION FACTOR FROM MOODY DIAGRAM",F
300   INPUT "ESTIMATE VALUE FOR  Loverd, DUE TO BENDS, VALVES, ETC.",Loverd
320   Lequiv=Loverd*D/12
340   Pdiff=F*Ro*(L+Lequiv)*Vel^2/D/2/32.2/144
341   IF Avg$="Y" THEN P1=P1hold
360   P2=P1-Pdiff
380   IF (P2<0) OR (Pdiff>.4*P1) THEN Negpressure
400   IF (Pdiff>.1*P1) AND (Pdiff<.4*P1) AND (Avg$="N") THEN Avgpressure
420   PRINT "     D     Pdiff     P2"
440   PRINT USING "XX,DD.DD,XXXXX,DDD.D,XXXXX,DDD.D";D,Pdiff,P2
460   INPUT "AGAIN?",Again$
480   IF Again$="Y" THEN GOTO 20
500   GOTO 720
520 Negpressure:  !
540   PRINT LIN(2),"PDIFF=";Pdiff
560   PRINT LIN(2),"PRESSURE DROP IS TOO GREAT, TRY AGAIN"
580   GOTO 20
600 Avgpressure: !
620   PRINT LIN(2);"AVERAGING PRESSURES....."
621   P1hold=P1
622   Avg$="Y"
640   P1hold=P1
660   P1=P1hold
680   P1=(P1+P2)/2
700   GOTO 140
720   PRINT LIN(3),"THAT'S ALL FOLKS"
740   END
```

FOR EQNS AND ASSUMPTIONS

REF: "COMPRESSED AIR" CHAPTER 26.

BY INGERSOLL-RAND

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PROJECT: MICROALGAE

DATE:

BY: DJ

OUTPUT FOR "GASHOL"

INPUTS:

CO_2 REQ'D = 1639 lbm/min

GAS PRESSURE AT PIPE HD	24.7 PSIA
GAS TEMP " " "	85 °F
ID PIPE	14" Ø
LENGTH	25540'
f = $(Re = 1.6 \times 10^6)$	0.011

OUTPUT

L/D = 2000	P DIFF = 8.32	P_2 = 16.4
L/D = 4000	P DIFF 8.99	P_2 = 15.71

14" Ø DELIVERY PIPE WILL PROBABLY BE ADEQUATE W/ 10 PSIG BLOWERS CAPABLE OF PUMPING 14600 SCFM AT REFINERY.

PROJECT: MICROALGAE

DATE:

BY: DJ

UTILITY COSTS

ELEC SYST. COSTS

ASSUME:

- EVERY THIRD POLE HAS TRANSFORMER.
- EVERY POLE SERVICES 4 PUMPS OR 2 PUMPS.
- 12 PUMP TRANSFORMERS = 150 KVA
- 6 " " = 75 KVA
- POLES ARE 30' TALL W/ 2 5' CROSS ARMS
- MOTOR CONTROL & BREAKERS INCLUDED IN INSTALLATION OF PUMPS.
- TWO TIMES 29,000 FT OF WIRE REQ'D + 50%
- EXTRA ELECT. COSTS FOR SHOP & LAB
- PRIMARY ELECTRICAL SYST COST - $75,000

REFERENCE NCE EXTRAPOLATION FROM
P 262-263
AND PERSONAL ESTIMATES.

FOR DETAILS OF COSTS SEE ATTACHMENTS.

SEWER SYST. CONNECTION

$ 20,000 (PERSONAL ESTIMATE)

TELEPHONE CONNECTION

$ 10,000 (PERSONAL ESTIMATE)

DATE: 2/12
PROJECT: MICROALGAE
BY: DJ

ELECTRICAL DISTRIBUTION SYSTEM.

RACEWAY MIXING PUMPS ARE PRIMARY LOADS IN THE RACEWAY AREA. OTHER ELECTRICAL LOADS DOWN THE RACEWAY ARE SUPPLIED BY GENERATOR TRUCKS.

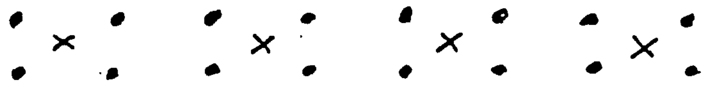
15 HP MOTORS ON PUMPS (11.2 KW)

$KVA = \frac{11.2}{\cos\theta}$ $\cos\theta$ = POWER FACTOR ASSUMED TO BE 0.90

KVA = 12.4 PER MOTOR
PUMP VOLTAGE = 480 V
MAX AMPERAGE = 35 AMP (1.5 OVERDRA

EACH PUMP ~ 100 FT FROM NEXT PUMP.

EACH DOT REPRESENTS PUMP.
EACH X A POLE



EACH POLE SUPPLIES 4 MOTORS OR 2 MOTORS DEPENDING ON LOCATION

POLE LOADS (REF. WATER DISTRIBUTION MAP)

BTN SECTIONS B-C	= 14	4	MOTORS EACH
SECTION A	= 10	2	" "
" E	= 9	4	" "
" F	= 2	4	" "
" D	= 8	2	" "
" G	= 12	2	" "
TOTAL 274	55		

PROJECT: MICROALGAE
DATE:
BY:

TOTAL NUMBER OF TRANSFORMERS REQ'D

12 MOTOR TRANSFORMERS (ONE TRANS. EVERY THIRD POLE)
150 KVA.

MATL	INSTL	TOTAL	TOTAL ALL
$ 4300	$ 951	$ 5251	$ 63012

6 MOTOR TRANSFORMER 75 KVA

MATL	INSTL	TOTAL	TOTAL ALL
$ 2800	$ 600	3400/UNIT	$ 22400

TOTAL NUMBER OF POLES REQ'D = 55
30' TALL W/ 2 5' CROSS BARS.

MAT'L	INST	TOTAL	TOTAL ALL
$ 160	$ 165	325/UNIT	$ 17875

· WIRE: ASSUME #4 ALUM WIRE (2 STRANDS)
OVER WHOLE FACILITY
29000 ft OF FACILITY + 50%

MATL/LF	INSTL/LF	TOTAL/LF	TOTAL ALL
0.21	0.36	0.36	$ 50400

OUTDOOR LIGHTING IN AREA NEAR BLDGS.
ASSUME: 30 LIGHTS (1000 WATT) ON 30' POLE

MATL	INSTL	TOTAL	TOTAL ALL
$ 1334	$ 838	2172/EA.	$ 65,170

TOTAL THIS PAGE $ 218 8

DATE:

PROJECT: MICROALGAE

BY: DJ

BUILDING ELECTRICAL

ASSUME ELECTRICAL COSTS INCLUDED IN COST OF BLDGS EXCEPT FOR SPECIAL HEAVY EQMT IN SHOPS AND LAB.

ADD $5.00/SF × 10000 SF = 50,000

PRIMARY ELECTRICAL INSTALLATION

ASSUME COST IS $75,000 (PERSONAL ESTIMATE)

TOTAL THIS SHEET = $125,000

TOTAL = $343,857

USE $345,000

PROJECT: MICROALGAE

DATE:

BY: DJ

WASTE DISCHARGE TRENCH COSTS

ASSUME:

- ALL CHANNELS CARRY 1/3 OF TOTAL FAC. VOL. IN 6 HRS TO SEA

REFERENCE:

		TOTAL
TRENCHING	20267 CY	
NCE P 166	4.5/CY	$ 91,201.50
CONCRETE	1869 CY	
NCE P 186	$235/CY	$ 439,215.00

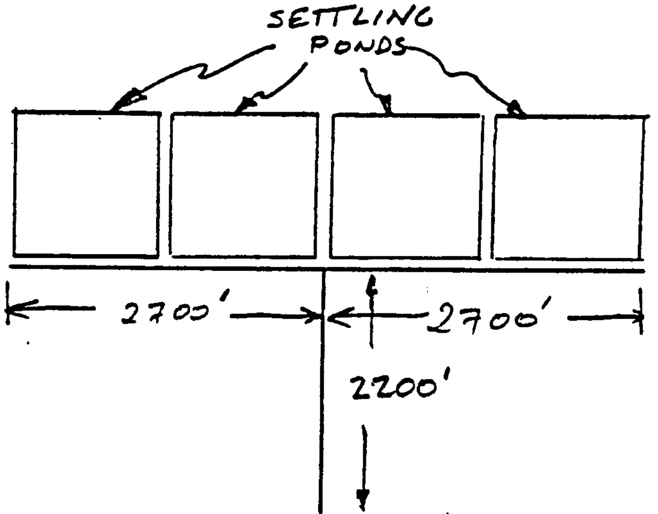
520

PROJECT: MicroAlgae

DATE: 2/11

BY: DJ

EFFLUENT DISCHARGE TRENCH (EWA SITE)



ALL CHANNELS MUST CARRY 1/3 OF TOTAL FACILITY VOLUME TO SEA IN 6 HRS

1/3 OF FACILITY VOLUME ~ 45,000,000 GAL.

TO CARRY THIS IN 6 HRS = 125,000 GPM

CHANNEL REQ'D: (SEE HARVEST WATER TRANSPORT FOR DERIVATION)

GPM	b	v	s
125K	10	1.7	$3.14(10^{-4})$
"	8	2.65	$1.04(10^{-3})$

← 8' OK

ASSUME:
6' DROP IN ELEV IN 4900' → $1.22(10^{-3})$ SLOPE

EXCAVATION = 547,200 CU FT (20,267 CY)

CONCRETE - 50464 CU FT (1869 CY)

PROJECT: MICROALGAE
DATE:
BY: DJ

EMERGENCY GENERATOR COST

ASSUME:

TOTAL COST OF GENERATORS IS EQUAL TO:

(FOR MOTOR STARTING LD.S)

TOTAL FACILITY KWH × 1.5 / 24 HRS / CAPACITY FACTOR $\left(\frac{\text{DAYS}}{\text{YR}}\right)$ / $\frac{\text{500 KW}}{\text{GEN.}}$ × # GEN.

ALL GENERATORS ARE 500KW

REFERENCE: NCE P 269.

500 KW GENERATOR 99,698 EA

USE 100,000 EA

PROJECT: MICROALGAE

DATE:

BY: DJ

BUILDING COSTS

ASSUME:

4000 SQ·FT OF OFFICE SPACE (20 OFFICE WKERS)
10,000 " " " GEN'L WAREHSE SPACE
10,000 " " " SHOP & LAB SPACE
8000 " " " EMPLOYEE SPACE (100 EMPLOYEES)
OFFICE SPACE COST ~ HOUSE COST

REFERENCE:

OFFICE SPACE COST BASED ON HOUSE COST/SF
NCE PAGE 158
HOUSE/SF ≅ \$50/SF

TOTAL ALL
\$200,000

WAREHOUSE (METAL SHELL TYPE)
\$25/SF (PERSONAL EST.)

TOTAL ALL
\$250,000

SHOPS + LAB (METAL SHELL, INCLUDES TOOLS & EQMT)
\$100/SF (PERSONAL EST.)

TOTAL ALL
\$1,000,000

EMPLOYEE SPACE (METAL SHELL BLDG, LOCKER, SHOWERS, CAFETERIA)
\$80/SF

TOTAL ALL
\$400,000

DATE:

PROJECT: MICROALGAE

BY: DJ

FENCE COST

ASSUME:

- ENTIRE SITE IS FENCED ALONG ROADWAYS AND ALONG BOUNDARIES TO TOWNS
- 60,200 ft OF FENCE
- 4' HIGH CHAIN LINK FENCE, 2" MESH 10' POLE SPACING

REFERENCE: NCE P. 177

MATL	LABOR	TOTAL	ALL TOTAL
$4.5	2.30	$ 6.80	$ 409,360

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(808) 259-5940

PROJECT: MICROALGAE
DATE:
BY: DJ

WATER SUPPLY COSTS

ASSUME:

- SEE ATTACHMENTS
- PUMPS NEAR SEA SHORE (ONEULA BCH PARK)
- 5000 GPM WELLS, 30' LIFT
- 10900' OF 16" Ø PVC
- 37600' OF 20" Ø PVC
- 9 PUMPS (AVG HEAD - 150' & 5000 GPM)
- 8 WELLS - 20" Ø LINED, DRILLED TO 140' (1 SPARE)
- 1 VALVE EVERY ½ MILE.

REFERENCE:

16" Ø PVC PIPE 19000' APACHE PLASTICS. (100PSI)

MATL	LABOR	TOTAL	TOTAL ALL
$ 13.56/LF	$ 6.00/LF	19.56	$ 371,640

20" Ø PVC PIPE 37600' APACHE PLASTICS (100PSI)

MATL'	LABOR	TOTAL	TOTAL ALL
20.56/LF	8.00/LF	28.56/LF	$ 1,073,856

9 PUMPS (PERSONAL ESTIMATE)
VERTICAL TURBINE PUMPS
$ 29000 EA $ 5000 TO INSTL — TOTAL ALL $ 175,000

8 WELLS REF: MR REYNOLDS ROSCOE-MOSS
140' DEEP × 20" Ø
DRILL, LINE, & TEST = 35,000 EA — TOTAL ALL $ 280,000

VALVES FRESNO VALVE
MANUAL VALVE 16" Ø & 20 Ø 2300 EA = $ 36800 — TOTAL ALL

520 | 3

DATE: 2/7
PROJECT: MICRO ALGAE
BY: DJ

WATER SUPPLY TO RACEWAYS (EWA)

IF ALL WATER IN FACILITY MUST BE EXCHANGED EVERY 3 DAYS (ASSUME 66 HRS - 6 HRS DOWN TIME)

THEN 3.5 RACEWAYS MUST BE DRAINED & REFILLED PER HOUR.

WATER FLOW IN RACEWAY ≅ 5000 GPM.

ASSUME: SLOPED RACEWAYS WHERE DRAIN & REFILL CAN OCCUR simultaneously.

520

PROJECT: MicroAlgae

DATE: 2/7

BY: DJ

WATER SUPPLY

WATER NEEDS: 204,486 m of raceway (half lengths)

204,486 × 2 = 408972 m running length.

ASSUME 0.12 m depth, 10 m width

VOL = 490,766 m^3 (1.2956 (10^8) GAL)

$$\underline{\text{EVAPORATION}} = 180\,\frac{cm}{yr}\,\frac{1\,yr}{365\,d} \times \frac{1\,day}{1440\,min}\,\frac{m}{100\,cm} \times$$

$$4{,}089{,}720\ m^2 \times \frac{264}{1\ m^3} = \underline{3698\ GPM}$$

FOR 3 DAY RETENTION TIME, 24 $\frac{HR}{DAY}$ Pumping

$$\frac{1.2956\,(10^8)\,GAL}{3\,day} \times \frac{1\,day}{1440\,min} = \underline{29991\ GPM}$$

TOTAL = 33689 GPM

SAY 35,000 GPM for 0.12 m depth

FOR 0.10 cm Depth

TOTAL = 24992 + 3698 = 28690 GPM

SAY 30,000 GPM for 0.10 m Depth

PROJECT: MICRO ALGAE
DATE:
BY: DJ

WATER SUPPLY SYSTEM CALCULATIONS

% OF WATER > 30' ELEV. ≅ 10.3%
20' < % OF WATER < 30' ≅ 65.9%
10' < % OF WATER < 20' ≅ 23.8%

PUMPS NEAR SEA SHORE; WELLS DELIVER 5000 GPM EA. WITH LIFTING HEAD OF 30'
(REF. MR REYNOLDS - ROSCOE-MOSS DRILLING CO.)

DELIVERY TO > 30' ELEV.

TOTAL WATER REQ'D SIMULTANEOUS DRAW. = 5 K GPM

16" Ø PIPE — 0.89 ft HDLOSS / 100 ft
10,000 ft PIPE REQ'D (16" Ø PVC - 100 psi)
1 PUMP (TOTAL HD = 89 + 30 + 30 = 149 ft)

DELIVERY TO > 20' BUT < 30' ELEV.

2 PIPELINES: ONE TO EACH SIDE OF WEAVER RD.

EAST SIDE:
FLOW: 10000 GPM
18,000 ft 20" PVC — 1.07 ft HDLS/100 ft
+ FLOW 5000 GPM
5000 ft 20" PVC — 0.32 ft HDLOSS/100 ft.
2 PUMPS (5000 GPM EACH) MAX HDLOSS = 192 + 50
= 242'

PROJECT: MICROALGAE

DATE:

BY: DJ

WEST SIDE

FLOW-10000 GPM
8600 FT 20" PVC HDLOSS 107 ft/100ft
FLOW - 5000 GPM
4000 FT 16" PVC HDLOSS 0.89 ft/100ft
2 PUMPS (TOTAL HDLOSS = 92 + 50 = 142')
ALL FOUR PUMPS FOR 20'-30' ELEV.
MUST PUMP AGAINST 242' HD FOR EAST SIDE.

DELIVERY TO > 10' BUT < 20' ELEV.

FLOW - 10000 GPM
6000 FT OF 20"Ø PVC HDLOSS=1.07'/100'
2 PUMPS (TOTAL HD LOSS = 64.2' + 40' = 104.2')

TOTAL PIPE NEEDS:

10900' - 16"Ø PVC
37600' - 20"Ø PVC

7 PUMP + 2 SPARES REQ'D
8 WELLS - (1 SPARES)
(AVG HEAD = 150')
VALVES IN LINES @ ½ MILE INTERVALS
16 TOTAL

PROJECT: MICROALGAE

DATE:

BY: DJ

CO_2 SUMP SPACING REQ'TS

HIGHEST PROD. RATE FOR LAW'S RACEWAYS.

248 gm/m²DAY AFDW (FOR SEVERAL HRS. IN MIDDAY LIGHT ON 3RD DAY OF CYCLE)

ASSUME:
- 50% CARBON BY WT
- UNIFORM PROD. THROUGH WATER COLUMN.
- CHANGE IN CO_2 CONC. IN WATER THROUGH SUMP 25% - 75% OF SATURATURATION.
- TOTAL SATURATION OF SW W/CARBON = $24 \frac{mg}{l}$

'C' - CONSUMPTION RATE

$$248 \frac{gm}{m^2 \cdot DAY} \times \frac{0.5\, gmC}{gm\ Biomass} \times \frac{1}{0.1\ m} \times (DEPTH)$$

$$\frac{1\, DAY}{12\, Hrs} \times \frac{1\, m^3}{1000\, l} \times \frac{1000\, mg}{gm} \times \frac{1\, hr}{3600\, sec} = 0.0289 \frac{mg\, C}{l \cdot SEC}$$

TIME REQ'D TO GO FROM 75% CO_2 SAT TO 25% CO_2 SAT,

$$t = \frac{12 \frac{mg}{l}}{0.0289 \frac{mg}{l \cdot sec}} = 415\ sec \sim \underline{7.0\ MIN}$$

FOR WATER FLOW AT 30 cm/sec

WATER WILL TRAVEL

$$0.30 \frac{m}{SEC} \times 415 = \underline{\underline{124.5\ m}}$$

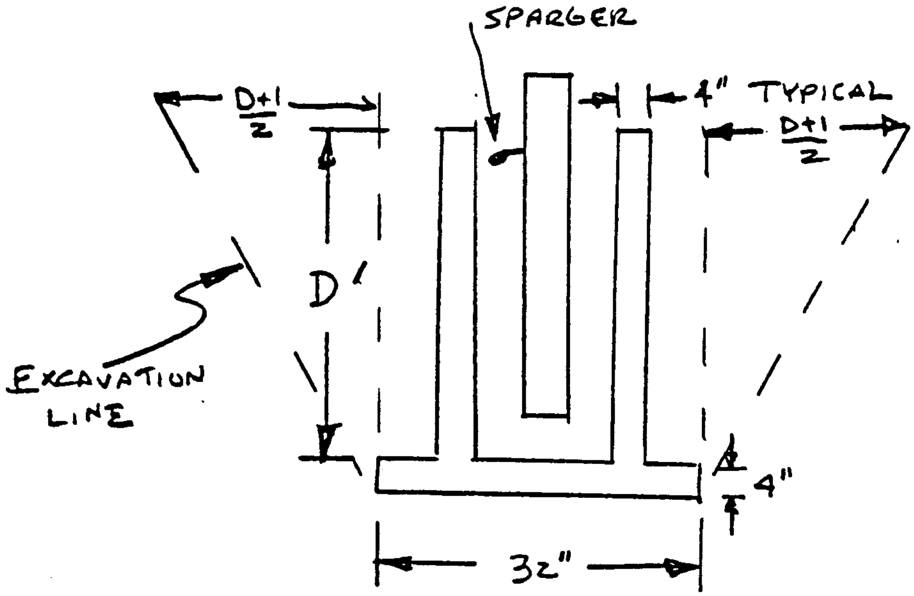
SPACE SUMPS AT THIS INTERVAL TO MEET MAX DEMAND.

PROJECT: MICROALGAE

DATE:

BY: DJ

CO2 SUMP DESIGN



10.5 M WIDE EXCAVATION

10 M WIDE CONCRETE

EXCAVATION:

$$\left[(D+1)\cdot \frac{32}{12}\times 10.5(3.28) + 2\left(\frac{D+1}{2}\right)^2\times 10.5(3.28)\right]/27$$

= 25.3 CY @ D = 1 M (3.28 FT)
= 161 CY @ D = 3 M (9.84 FT)

CONCRETE

$$\left[\frac{4''}{12}\cdot D\times 10(3.28) + \frac{32''}{12}\times \frac{4''}{12}\times 10(3.28)\right]/27$$

= 3.5 CY FOR D = 1 M
= 9.6 CY FOR D = 3 M

CENTER BD (CONCRETE)

$$\left[\frac{4''}{12}\times 10\cdot(3.28)\cdot D\right]/27$$

= 1.62 CY FOR D = 1 M
= 3.98 CY FOR D = 3 M

DATE:
PROJECT: MICROALGAE
BY: DJ

CO₂ SUMP SPACING REQ'TS

HIGHEST PROD. RATE FOR LAW'S RACEWAYS.

$248\ \mathrm{gm/m^2 \, DAY}$ AFDW (FOR SEVERAL HRS. IN MIDDAY LIGHT ON 3RD DAY OF CYCLE)

ASSUME:
- 50 % CARBON BY WT
- UNIFORM PROD. THROUGH WATER COLUMN.
- CHANGE IN CO_2 CONC. IN WATER THROUGH SUMP 25% - 75% OF SATURATURATION.
- TOTAL SATURATION OF SW W/CO_2 = $24\ \frac{mg}{\ell}$

'C' - CONSUMPTION RATE

$$248\ \frac{gm}{m^2 \cdot DAY} \times \frac{0.5\ gmC}{gm\ Biomass} \times \frac{1}{0.1\ m\ (DEPTH)} \times$$

$$\frac{1\ DAY}{12\ Hrs} \times \frac{1\ m^3}{1000\ \ell} \times \frac{1000\ mg}{gm} \times \frac{1\ hr}{3600\ sec} = 0.0289\ \frac{mg\ C}{\ell \cdot SEC}$$

TIME REQ'D TO GO FROM 75% CO_2 SAT TO 25% CO_2 SAT,

$$t = \frac{12\ \frac{mg}{\ell}}{0.0289\ \frac{mg}{\ell \cdot sec}} = 415\ sec \sim \underline{7.0\ MIN}$$

FOR WATER FLOW AT 30 cm/sec

WATER WILL TRAVEL

$$0.30\ \frac{m}{SEC} \times 415 = \underline{\underline{124.5\ m}}$$

SPACE SUMPS AT THIS INTERVAL TO MEET MAX DEMAND.

! THIS NEEDS OPTIMIZATION & STUDY IN EXP. SYST. !

DATE:

PROJECT: MICROALGAE

BY: DJ

ROADWAY COSTS

ASSUME:

- 234 RACEWAYS OF 874 AVG HALFLENGTH
- 5 M ROAD BETWEEN ALL RACEWAYS,
- OTHER FEEDER ROADS ARE 20 & 40 M WIDE — TOTAL AREA EWA SITE = 27.8 HA.

REFERENCE: NCE P. 167.

ASSUME 1" OF SOIL OVER ALL ROAD AREA MUST BE REDISTRIBUTED.

$$@\ 2.65/\text{CY} \times \frac{\text{CY}}{27\,\text{ft}^3} \times 1/12\ \text{ft} = \$\,0.0082/\text{SF}$$

$$\text{OR} \quad \underline{\underline{\$\,0.88/\text{SM}}}$$

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PROJECT: MICROALGAE

DATE:

BY: PJ

MIXING PUMP COST

ASSUME:

- TOTAL DYNAMIC HEAD 5-8 FT.
- WET PIT PROPELLOR PUMP WILL NOT HARM ALGAE
- ~5000 GPM CONTINUOUS PUMPING FLOW

REFERENCE:

CONVERSATION W/ MARK BOUDET OF M & W PUMP CO.

16" Ø DISCHARGE WET PIT PROPELLOR PUMP STAINLESS STEEL BOWL, PROPELLOR, SHAFT ETC.

@ 720 RPM EFF = 84% (25% PITCH CHANGE IN PROP.)

COST $20,285 LIST

EXPECT 30% REDUCTION FOR LARGE ORDER

TOTAL 14,200 EACH.
ADD 800 SHIPPING (PERSONAL ESTIMATE)

ASSUME! $5000 INSTALLATION (PERSONAL ESTIMATE)

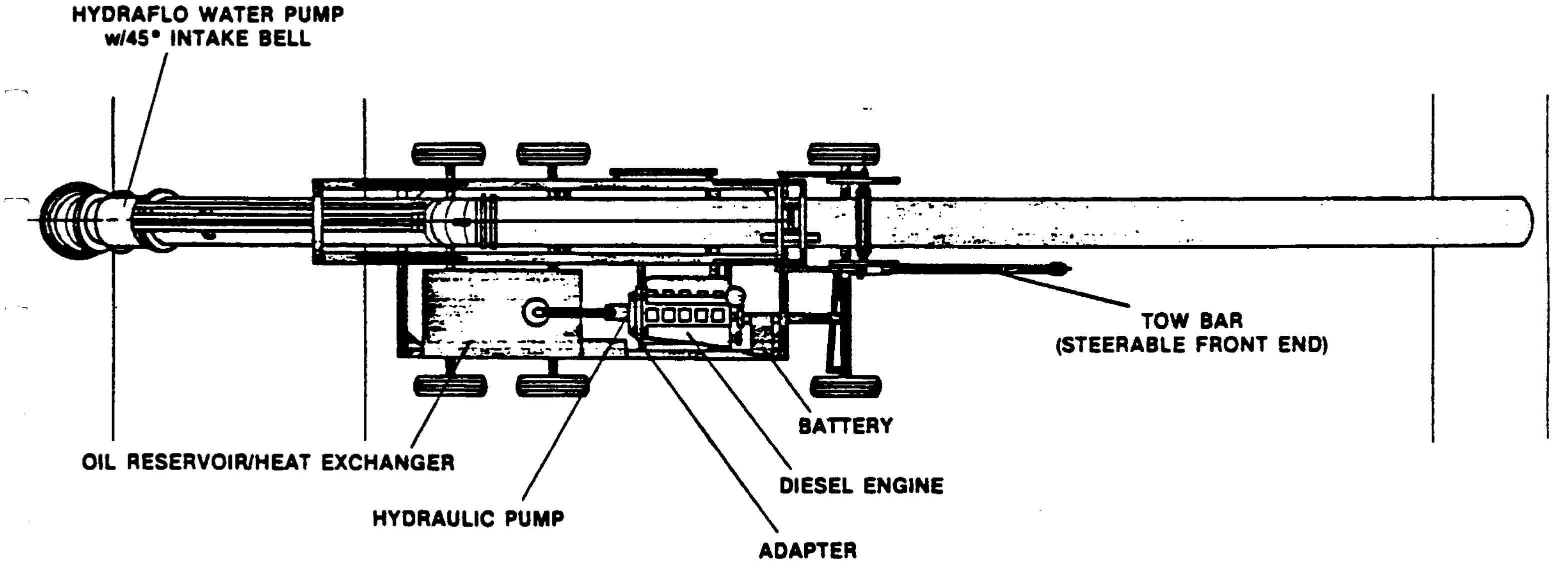
TOTAL PER PUMP = $20,000

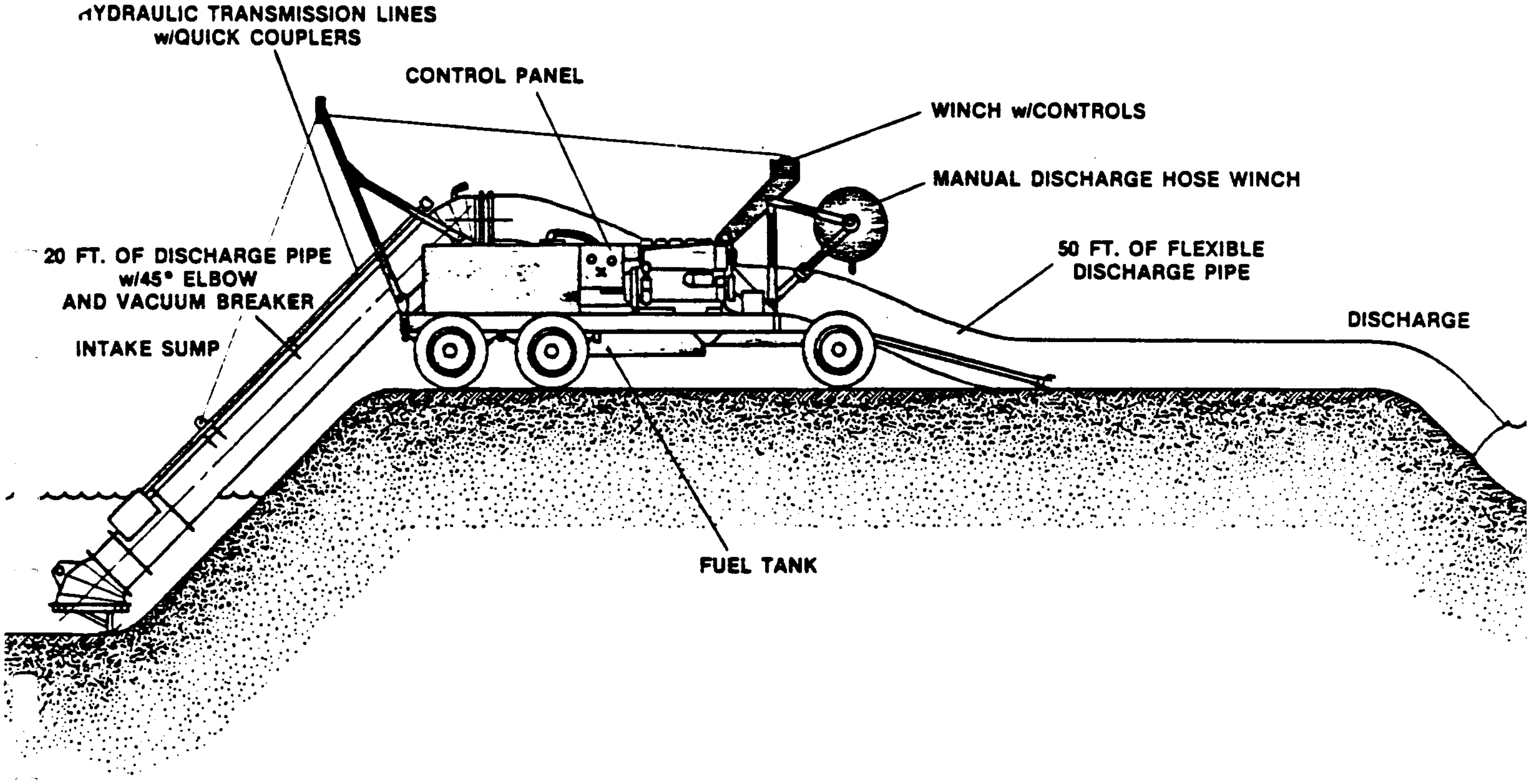
M&W PUMP CORPORATION

TYPICAL APPLICATION FOR

MOBILE DIESEL DRIVE UNIT

WITH 45 DEGREE HYDRAFLO WATER PUMP





SEE DIMENSIONS ON SHEET, SECTION II, E

DATE:
PROJECT: MICROALGAE
BY: DJ

GRADING COSTS

ASSUME:

- FOR ROUGH GRADE, 1" OF SOIL MUST BE REDISTRIBUTED OVER ENTIRE RACEWAY SURFACE. – SURFACE = ROCK + EARTH CONGLOMERATES.

  (1")
  $1748\,m \times 10m \times 0.0254m = 444.0\ m^3$
  (582 CY)

- ENTIRE AREA OF RACEWAY MUST BE FINE GRADED – 17480 m^2 (188,057 SF)

REFERENCE:

ROUGH GRADE NCE P167
ROADWAY EXCAVATION & FILL, 6" LIFTS, SCRAPER W/ OPERATOR, COMPACTED TO 95% AASHO

MAT'L	LABOR	TOTAL	TOTAL ALL
1.95/CY	0.70/CY	$ 2.65/CY	$ 1591/RCWY

FINE GRADE NCE 182 FOR SLABS

MAT'L	LABOR	TOTAL
0.04	0.019	0.059

FOR LARGE JOB ASSUME COST COULD BE REDUCED TO 40% OF THIS (PERSONAL ESTIMATE)

$0.059 \times 0.40 = \$0.023$

TOTAL ALL
$ 4325/RCWY

DATE:
PROJECT: MICROALGAE
BY: DJ

NUTRIENT SYSTEM COSTS

ASSUME:

- 50 GM/m^2·DAY AFDW
- 8.0% OF AFDW IS NITROGEN
- 0.5% OF " " PHOSPHORUS
- NH_3 CONC. IN NUTRIENT SOLN 10% BY WT.
- 10-34-0 " " " " 2% BY WT.
- AVG FLOWRATE THROUGH FEED LINES = 35 GPM (TO WHOLE FACILITY)
- AVG HEADLOSS TO ANY RACEWAY ~ 47'
- 29000' OF 3" Ø PVC PIPE REQ'D
- 2 PUMPS 35 GPM, 47 ft HD.

REFERENCE:

29000' OF 3" Ø PVC (AQUACULTURE ASSOC. EST)

MAT'L	INSTL (NCE P172)	TOTAL	TOTAL ALL
1.02	2.00	3.02	$ 87580

MIXING TANK (PERSONAL ESTIMATE)
$ 10,000

2 PUMPS 35 GPM, 47 ft HD

MAT'L	INSTL	TOTAL	TOTAL ALL
$562	$295	857/EA	$ 1714

DATE: 2/11

PROJECT: MICROALGAE

BY: DJ

NUTRIENT DISTRIBUTION SYSTEM.

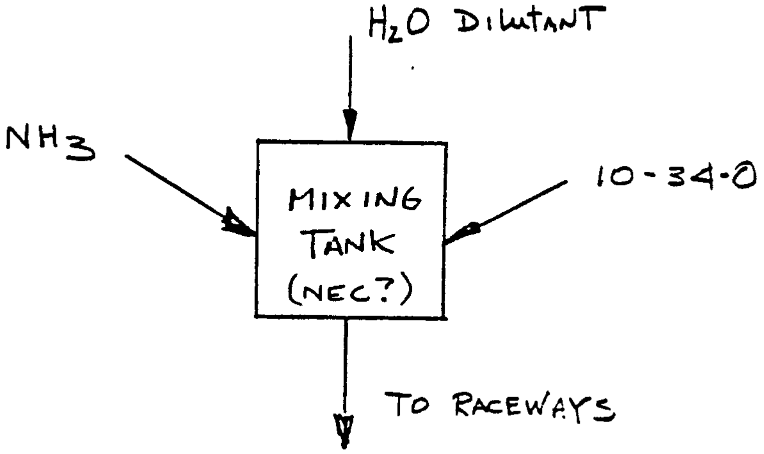
ASSUME: $50 \frac{gm}{m^2 \cdot day}$ → FACILITY PROD.

$17,067 \frac{Kg}{HR}$ (daytime GROWTH ONLY)

8.0% OF PRODUCT IS N → 1355 Kg/HR
0.5% " " " P → 85.3 kg/HR

WESTERN FARM SERVICE FERTILIZERS:

10-34-0 10% N & 34% P_2O_5 (14.8% P)
NH_3 82% N



ASSUME: NH_3 CONC. BY WT TO AVOID PRECIPITATION IS 10% (BASIS: HOUSEHOLD AMMONIA IS 5% BY WT.)

MIXTURE = $13650 \frac{Kg}{HR}$ H_2O + $1365 \frac{Kg}{HR}$ N + $85.3 \frac{Kg}{HR}$ P.

IN TERM OF ACTUAL FERTILIZERS:

MIXTURE: 13650 Kg H_2O + 1594 Kg NH_3 + 576. Kg 10-34-0

PROJECT: MICROALGAE

DATE:
BY: DJ

IF FINAL MIXTURE HAS DENSITY APPROX. EQUAL TO SEAWATER ($1025 \frac{kg}{m^3}$)

$Vol = 15.4 \frac{m^3}{HR}$ (70 GPM) FOR WHOLE FACILITY

Avg Flowrate IN ANY PIPE LINE IN FACILITY WILL BE <u>35 GPM</u>

35 GPM FOR 3"Ø PVC HD LOSS/100 ft = 0.36

70 GPM FOR 3"Ø " " " = 1.22

FOR 18,000 ft PipeLINE (LONGEST IN FACILITY)
HEAD LOSS WILL BE 64.8 FT. (Friction)
\+ 30 FT (ELEVATION)
~95 FT (TOTAL)

AVG HD LOSS WILL PROBABLY BE ABOUT HALF OF THIS = **47 ft.**

DATE:

PROJECT: MICROALGAE

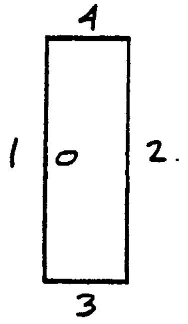
BY: DT

H_2O SUMP

ASSUME:

15 CM THK REINFORCED CONCRETE, ON WALLS.
EXCAVATION 5 m × 2m. × 10m = 100 m^3 (131CY)

4 WALLS:



	CONCRETE REQ'D
1.	4.35 m^3
2	3.6 m^3
3.	1.74 m^3
4.	1.74 m^3
	11.43 m^3 (15CY)

BASE SLAB - 3.6 × 10 × 0.1 = 3.6 m^3
(4.7CY)

REFERENCE.

EXCAVATION NCE P. 166

MATL	LABOR	TOTAL	TOTAL ALL
1.76	2.75	4.5 /CY	$591

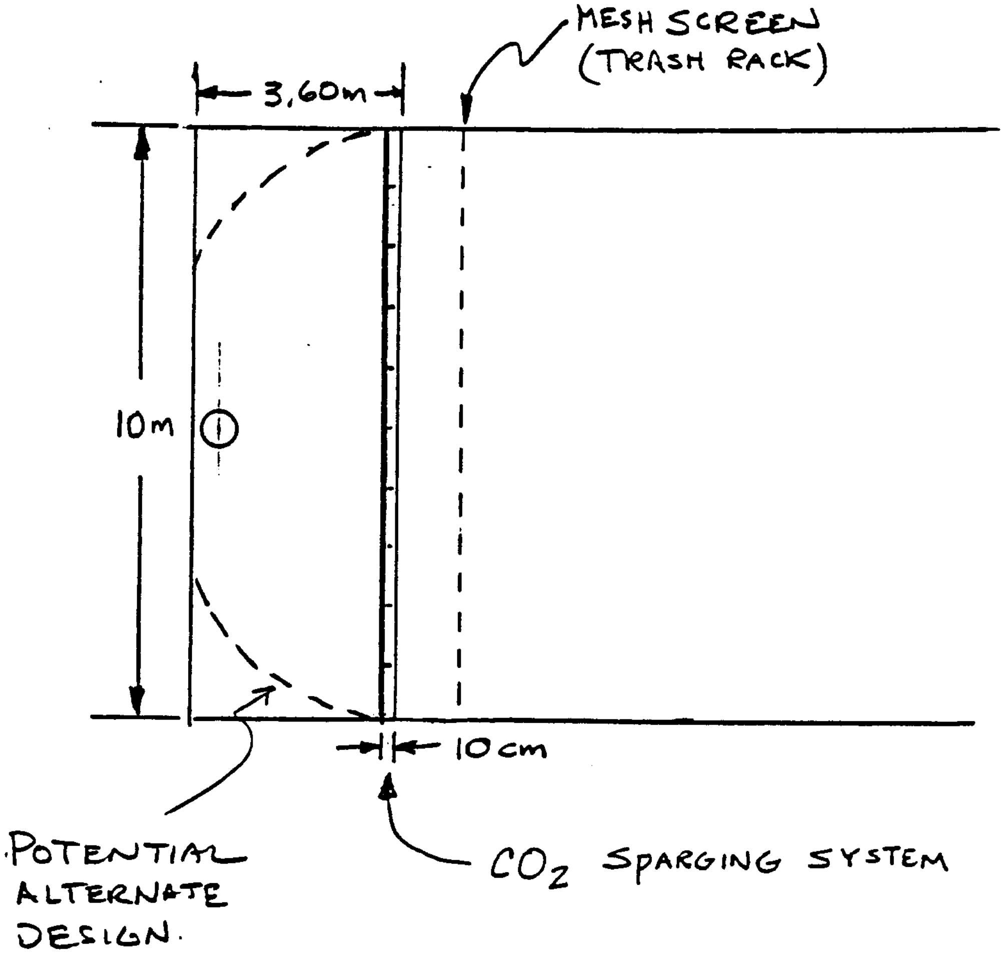
FOUNDATIONS NCE P 186

MAT'L	LABOR	TOTAL	TOTAL ALL
1.19	1.17	$235	$3525

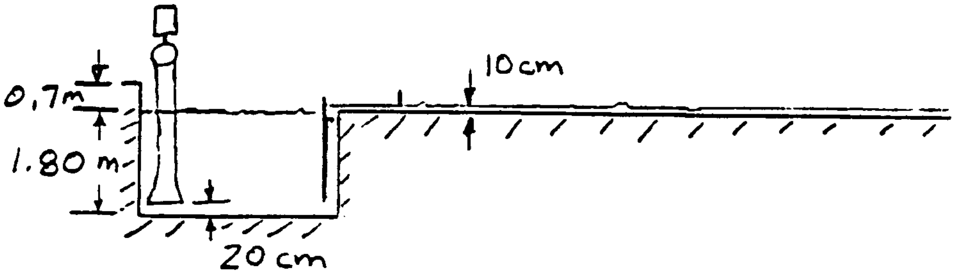
BASE SLAB NCE P 185

TOTAL	TOTAL ALL
$109	$513

TOTAL $4629



ALL SUMP WALLS ARE 10 CM THK REINFORCED CONCRETE.



SUMP DESIGN. (HYDRAULIC INST. STDS)

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(808) 259-5940

DATE:

PROJECT: MICROALGAE

BY: DJ

RACEWAY CUT & FILL COSTS

ASSUME:

- CALCULATIONS MADE FOR 1600 m RUNNING LENGTH RACEWAY CAN BE LINEARIZED TO COVER ANY RACEWAY.
- 8 cm HDLOSS / 100 m
- WATER DEPTH = 0.12 m
- SEE ATTACHED CALCULATIONS FOR OTHER ASSUMPTIONS

REFERENCE: NCE P167

ROADWAY EXCAVATION & FILL, 6" LIFTS, SCRAPER W/OPERATOR COMPACTED 95% AASHO.

FOR ROCK & EARTH CONGLOMERATES

MAT'L	LABOR	TOTAL
1.95/CY	.70/CY	2.65/CY

FOR CUT & FILL FOR SLOPE - 2809 CY

TOTAL COST
$7444

FOR CUT & FILL FOR BERMS 1566 CY

TOTAL COST
$4150

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PROJECT: MICROALGAE

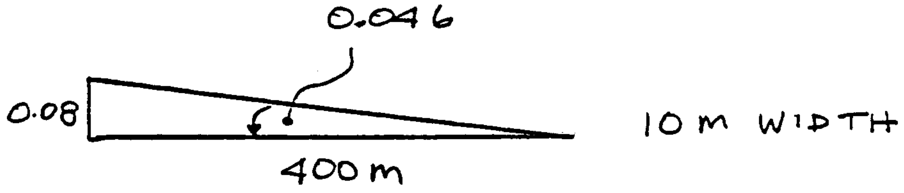
DATE:

BY: DJ

CUT & FILL TO ACHIEVE SLOPED RACEWAY

ASSUME:

- 8 CM HEADLOSS PER 100 M RUNNING LENGTH
- DIRT REMOVED AT LOW END OF EACH SIDE OF RACEWAY WILL BE SUFFICIENT TO FILL HIGH END.
- 10% EXTRA NEEDED FOR COMPACTION



EXCAVATION PER 1600 M RACEWAY =

$$2\left[10\,\text{M}\left[400\,\text{m}\times\frac{400}{2}\,\text{TAN}\,0.046\right]\right]/0.90$$

$$= 1440\ \text{m}^3 \quad (1886\ \text{CY})$$

THIS SEEMS VERY OPTIMISTIC SINCE OTHER CUT & FILL WILL ALWAYS BE REQ'D TO ESTABLISH SOMEWHAT LEVEL CONDITIONS FROM START.

ADD 50% → 2809 CY

53D 1

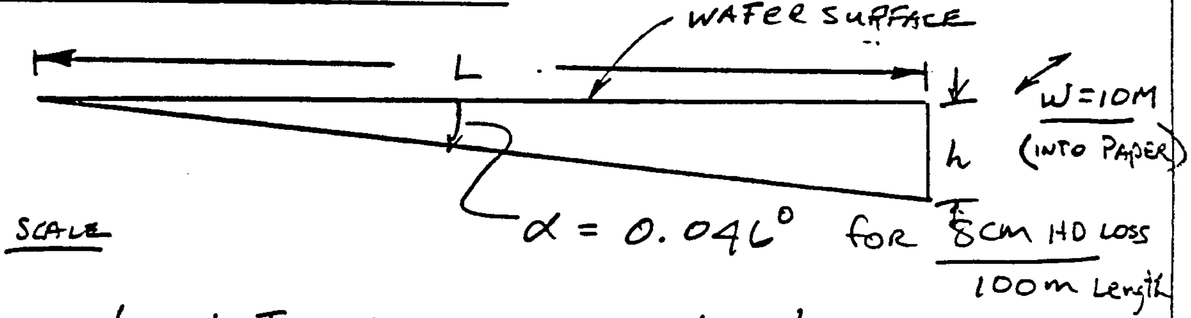
DATE: 2/9
PROJECT: MICROALGAE
BY: DJ

ADDITIONAL BERM HEIGHT FOR WATER COLLECTION DURING PUMP SHUT DOWN

TOTAL WATER VOLUME: @ 12 cm depth

$$VOL = 0.12\,m \times 1600\,m \times 10\,m = \underline{\underline{1920\,m^3}}$$

SIDE VIEW OF RACEWAY



NOT TO SCALE

$$h = L \tan\alpha \qquad \text{OR} \qquad L = \frac{h}{\tan\alpha}$$

VOLUME OF WATER IN THIS SLOPING POOL

$$VOL = \tfrac{1}{2}(h \cdot L) \cdot W$$

SO

$$h = \sqrt{\frac{2\,(VOL)\tan\alpha}{W}} \qquad \text{OR} \qquad L = \sqrt{\frac{2 \cdot VOL}{W \cdot \tan\alpha}}$$

FOR $VOL = 1920\,m^3$ $W = 10\,m$ $\alpha = 0.046^\circ$

$h = 0.56\,m$ $L = 698\,m$

TO BE SAFE:

SET BERM Height AT $\underline{h = 0.7\,m}$
AND INCREASE BERM HEIGHT PROPORTIONALLY
FROM 700 M AWAY 300 FROM PUMP SUMP

SLOPED POND BERM CONSTRUCTION:

FOR SIDE FLOWING AWAY FROM PUMP DISCHARGE:

LH SIDE

$$\text{VOL} = \left(\frac{0.48 \times 0.24}{2}\right) \times 800\,m = 46.0\ m^3$$

RH SIDE

$$\text{VOL} = \left(\frac{0.96 \times 0.24}{2}\right) \times 800 = 96.2\ m^3$$

$$\left.\begin{matrix} 46.0\ m^3 \\ 96.2\ m^3 \end{matrix}\right\} \underline{142.2\ m^3}$$

FOR SIDE FLOWING TOWARD PUMPING SUMP.

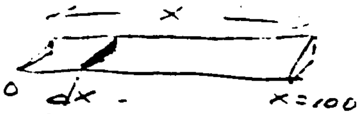
CROSS-SECTION 100 m from TURNAROUND.

LH SIDE

$$\text{VOL} = \frac{0.96 \times 0.24}{2} \times 100 = 12.0\,m^3$$

RH SIDE

$$\text{VOL} = \int_0^{100} \frac{b \cdot h}{2} \cdot dx$$



$$b = 0.48 + \frac{0.16}{100}(x)$$

$$h = 0.24 + \frac{0.08}{100}(x)$$

PROJECT: Microalgae

DATE:

BY:

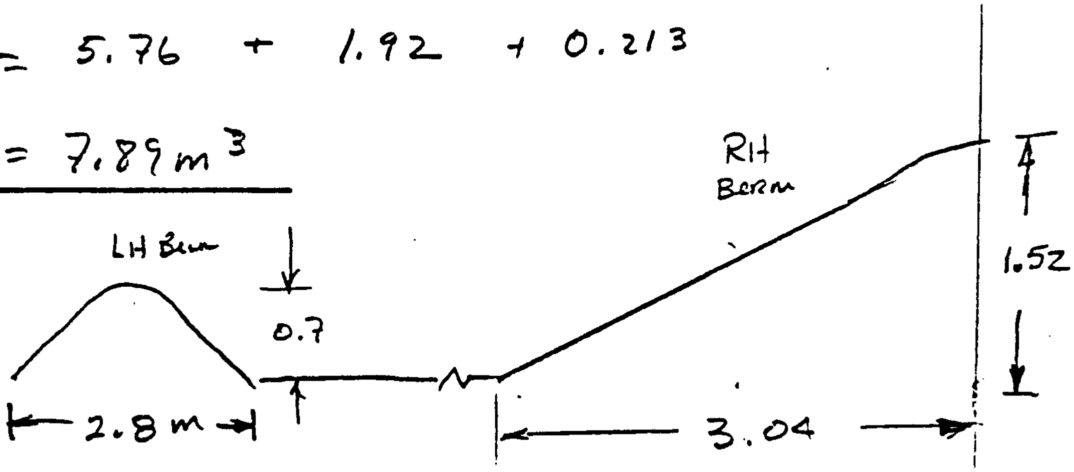
RH SIDE CONT

$$VOL = \frac{1}{2}\int_0^{100} (0.48 + 0.0016\,x)(0.24 + 0.0008(x))\,dx$$

$$= \frac{1}{2}\int_0^{100} 0.1152\,dx + \frac{1}{2}\int_0^{100} 7.68(10^{-4})\,x\,dx + \frac{1}{2}\int_0^{100} 1.28\,(10^{-6})\,x^2\,dx$$

$$= 5.76 + 1.92 + 0.213$$

$$\underline{= 7.89\,m^3}$$



CROSS SECTION JUST UPSTREAM
OF PUMP SUMP.

LH SIDE

$$VOL = \int_0^{700} \frac{b \cdot h}{2} \cdot dx \qquad b = 0.96 + \frac{1.88}{700}(x)$$

$$h = 0.24 + \frac{0.46}{700}(x)$$

$$VOL = \frac{1}{2}\int_0^{700} 0.2208\,dx + \frac{1}{2}\int_0^{700} 1.28\cdot(10^{-3})\,x\,dx + \frac{1}{2}\int_0^{700} 1.76(10^{-6})\,x^2\,dx$$

$$= 77.3 \quad 156. \quad + 100.9$$

$$\underline{= 334\ m^3}$$

RH SIDE

$$Vol = \int_0^{700} \frac{b \cdot h}{2} \cdot dx \qquad b = 0.64 + \frac{2.4}{700}(x)$$

$$H = 0.32 + \frac{1.2}{700}(x)$$

$$VOL = \frac{1}{2}\int_0^{700} 0.2048\, dx + \frac{1}{2}\int_0^{700} 2.194(10^{-3})\, x\, dx \frac{1}{2}\int_0^{700} 5.88(10^{-6})\, x^2 dx$$

$$= 71.7 + 268.8 + 336.1$$

$$= \underline{676.6\ m^3}$$

TOTAL:

SIDE FLOWING AWAY FROM PUMP DISCHARGE = 138.2 m^3

SIDE FLOWING TOWARD PUMPING SUMP =

LH 1ST 100 m = 11.5 m^3
RH " " = 7.89 m^3
LH next 700 m = 331 m^3
RH next 700 m = 677 m^3

1027 m^3

TOTAL = 1165 m^3

ADD 5% FOR END BERMS AND ASSUME COMPUTED VOLUME IS ONLY 90% OF REQUIREMENT AFTER COMPACTION.

VOL = $\frac{1025 \times 1.05}{\ }$ = $\underline{1195\ m^3}$ (1566 CY/

DATE:

PROJECT: MICROALGAE

BY: DJ

CO2 STORAGE COST

ASSUME:

CO_2 STORAGE AS COMPRESSED LIQ @ 839 PSI
6' DIA CYL – PRESSURE VESSEL
100 CU FT (490,000 lb) STEEL REQ'D FOR 1 DAY VESSEL.

REFERENCE: NCE P194

STEEL COST

MAT'L	WELDED INSTL	TOTAL
0.51/lb	0.13/lb	0.64/lb.

SHIPPING 37/TON → 0.02/lb

0.66/lb

FOR ONE DAY → $ 322,006
490,000 lb STEEL

$$\frac{\text{ONE DAY STORAGE COST}}{\text{ONE DAY } CO_2} = \frac{322006}{825,800} = \$\,0.39/\text{lb } CO_2$$

DATE:

PROJECT: MICROALGAE

BY: DJ

CO$_2$ STORAGE REQ'TS

CO$_2$ STORAGE AS COMPRESSED LIQ.

DENSITY 839 PSI – $47.35 \frac{\text{lbm}}{\text{ft}^3}$ 70°F.

1 DAY = 17420 CU FT.

(HY 100,000)

6' DIA. CYL, ALLOY STEEL $\sigma_{YIELD} = 100(10^3)$ psi

$\sigma_{ALL} = 50(10^3)$ psi

$$\sigma_{ALL} = \frac{P_i \cdot D}{2T} = \frac{839 \cdot 6'}{2\ T}$$

$$T = 2517/\sigma_{ALL} = \underline{\underline{0.05''}}$$ FOR ALLOY STEEL

6' DIA CYL HOLD $\frac{28.3 \text{ CU FT}}{LF} \rightarrow \sim 616$ FT FOR 1 DAY STORAGE.

VOLUME OF STEEL

$$616 \cdot 6' \cdot \pi \cdot \frac{0.05}{12} + 2\left(6^2 \frac{\pi}{4} \cdot \frac{0.05}{12}\right) \cong 50 \text{ CU FT}$$ OF STEEL

ASSUME ANOTHER 50 CU FT REQ FOR EXT. STRUCTURE

100 CU FT × 490 lb/FT^3 = 490,000 lb

FOR 1 DAY STORAGE

APPENDIX E

Anaerobic Digester Price Quote

Atara, Inc.

ATARA

ATARA INCORPORATED
277 FOREST AVE., PARAMUS, N.J. 07652
TEL.: (201) 261-0066
TELEX: 135-142

October 29, 1984

Aquaculture Assoc.
1110 Richards Street, Room 207
Honolulu, Hawaii 96813

Att: Mr. Fred Mecher

Subject: Solar Energy Research Institute
Microalgae Production Facility
Anaerobic Digestion Process

Gentlemen:

In accordance with our conversation of October 24, 1984 please find enclosed our recommended design for the anaerobic digestion of the byproduct of a 1,000 acre microalgae production facility. Our design includes four (4) 100' dia. anaerobic digesters. We would estimate a net digester gas production of 2,000,000. cu. ft. per day based on the assumptions which we had discussed via the telephone and as shown on the enclosure.

Gentlemen, we trust that the enclosed information will enable you to evaluate the economics of anaerobic digestion for the generation of methane gas from microalgae. Should you require any additional information to make your evaluation or have any questions concerning our preliminary design, please do not hesitate to contact the undersigned at our office in Paramus.

Very truly yours,

ATARA, INCORPORATED

Jerry DeVos
Sales Manager

JD/as
encl.

MANUFACTURERS OF ENERGY EFFICIENT ANAEROBIC SYSTEMS
TECHNICAL REPRESENTATIVES IN MAJOR CITIES IN THE USA AND CANADA

10/29/84

ATARA INCORPORATED

DESCRIPTION & ESTIMATE

ATARA DIGESTER SYSTEM

FOR: Solar Energy Research Inst.
Microalgae Gas Production Facility

ENGINEER: Aquaculture Assoc.
Honolulu, Hawaii

We propose to furnish the following equipment:

Item I - Digestion Tanks

1. 48 complete Aero Hydarulics Heating Mixing Guns for the four (4) 100' diameter digester(s). Each gun shallconsist of a non-clog piston bubble generator, a 24" diameter stack, hot water jacket, floor mounted support bracket, plus piping and fittings as shown on Drawing — . Units shall be prepared by sandblasting followed by 2 shop coats of epoxy paint.

2. Six (6) complete gas compressor assemblies. (Four (4) operating, two (2) standby). Each compressor assembly shall consist of a liquid ring rotary compressor, all bronze construction rated at 275 SCFM at 15 PSIG, and shallbe complete with 25 HP explosion-proof motor, discharge moisture separator with float switches, inlet flame arrester, inlet sediment trap, seal water line accessories, high pressure drip trap, discharge check valve, conductive belts, guards, baseplate, inlet and outlet pressure gauges and high/low pressure safety controls.

3. Four (4) wall-mounted control assemblies consisting of combination starter and circuit breaker, and system operating lights and switches.

4. Four (4) Gas Flow Balancing unit consisting of one 4½" pressure gauge, balancing valve, and isolation valve for each Aero Hydraulics Mixing and Heating Gun.

5. Four (4) thermostat(s), to be inserted into the digester to control temperature and heating cycles of the digester.

6. One (1) hot water boiler to deliver 7,000,000 BTUH. The boiler is complete with controls, safety devices, and pump to circulate hot water to the digester. Boiler shall be designed to burn digester gas and natural gas .

DESCRIPTION & ESTIMATE CONTINUED
FOR: Solar Energy Research Inst.

7. Digester Tank Covers

No. of Tanks Four (4)

Dia. of Tanks 100'-0"

Dia. of Cover 99'-0"

Type of Cover (2)Single Deck Vertically Guided Gasholder, (2) Fixed Covers

Operating Pressure 10.0" w.c.

8. Insulated Steel Digestion Tanks complete with connections for external piping.

9. Gas Scrubber. For removal of H_2S and mercaptans only

10. Prefabricated Operations Building

Our estimated price to provide a complete Atara Digester System as described above is $2,400,000.00 to $3,000,000.00.

Does not include the following:

Concrete Base for Steel Tanks
External Piping
External Electrical
Erection of Tanks and Covers
Field Painting
Site Work
Pumps, Valves, etc.

Items other than specificatlly described above.

October 29, 1984

ATARA INCORPORATED

PRELIMINARY DESIGN

ATARA ANAEROBIC DIGESTER SYSTEM

PROJECT: Solar Energy Research Inst.
Microalgae Gas Production Facility

ENGINEER: Aquaculture Assoc.
Honolulu, Hawaii

Attn: Mr. Fred Mecher

REP: None

DESIGN BRIEF - DIGESTER SYSTEM:

Basic Information:

Type of Waste: Microalgae
Min. Hydraulic Retention Time: 10 days
Max. VSS Loading Rate: 0.25 lb. VSS/ft^3/day
Volatile Solids Conc: 90%
Digester Feed Temp. 30°c (86°F)
Microalgae Volume to Digester: 50,000 dry tons/year @ 5% solids
Mixing Requirement: Minimum active volume of 90%
Digester Temperature: 95°F. $\pm\frac{1}{2}$°F at any point in tank

I Min. Digester Volume Required: 880,000 ft.^{3}@ 10 day HRT
986,000 ft.^{3}@ .25 lb vss/ft^3

Select 986,000 ft.^{3}

Assume 4 digester each @ 246,500 ft.^{3}

Anaerobic Digester Section and Sizing:

4 100 ft. dia.(New)
Primary Anaerobic Digesters*
equipped with mixing and heating

Each digester complete with:
(Atara AH Mixing and Internal Heating

Fixed Cover(s) 2
Vertically Guided Gasholder(s) 2
Spirally Guided Gasholder(s)
Maximum SWD 31'-6"
Minimum SWD 27'-0"

II Design of Atara Digester Mix/Heat System

No. of Atara AH Heating/Mixing Guns 12 - 24" dia.
Submergence at minimum liquid level 3'
Submergence at maximum liquid level 6'-6"

Location of Units: 3 units at 17' radius, 120° apart
9 units at 34' radius, 40° apart.

III Digester Heating Requirements

Heat required for feed material (@ 30°c) = 2,000,000 BTUH
Estimated Tank Losses (Fully insulated tank)= 1,500,000 BTUH

Total Supplemental Heat 3,500,000 BTUH

October 29, 1984

ATARA INCORPORATED

ENERGY EVALUATION
ATARA ANAEROBIC DIGESTER SYSTEM

FOR: Solar Energy Research Inst.
Microalgae Gas Production Facility

ANTICIPATED GAS PRODUCTION: (Assuming 60% volatile solids destruction and 15 cu. ft. of digester gas per lb. volatile solids destroyed).

137 tons X 90% volatile X (2,000 lb.) x (15 cu.ft./lb)

x (60%) = 2,200,000 cu. ft./day @ 60% methane

PLANT ENERGY CONSUMPTION

Liquid Pumps	- 20 HP	(Assumed)
Gas Mixing	-100 HP	
Water Recirculation	12 HP	
Estimated operating power	132 HP	

POWER COST (@ 6¢/kwh) = 132 HP x .06 x .746 x 24

= $140/day

Gas Required for Tank Heating

3,500,000 BTU/hr Avg. Boiler Output @ 80% efficient - 4,400,000 BTU/hr input

gas consumption = 7,333 CFH or 175,0000 ft. ^{3}/day

Net Energy Produced = 2,200,000 ft. ^{3}/day
175,000 ft. ^{3}/day
2,000,000 ft. ^{3}/day @ 60% methane

Net Worth @$6/1000 ft.^{3} methane = $7200/day

Less Power Cost - 140

Net Energy Cost $7060 ± /day

APPENDIX F

U.S. Patent No. 4,338,199

Modar, Inc.

Supercritical Water Combustion

United States Patent [19]

Modell

[11] **4,338,199**

[45] **Jul. 6, 1982**

[54] **PROCESSING METHODS FOR THE OXIDATION OF ORGANICS IN SUPERCRITICAL WATER**

[75] **Inventor:** Michael Modell, Cambridge, Mass.

[73] **Assignee:** Modar, Inc., Natick, Mass.

[21] **Appl. No.:** 147,946

[22] **Filed:** May 8, 1980

[51] **Int. Cl.³** C02F 1/72

[52] **U.S. Cl.** 210/721; 210/761

[58] **Field of Search** 210/761, 762, 721, 722, 210/774, 766; 48/209, 202, 210

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,207,572	9/1965	Saul	210/761 X
3,876,497	4/1975	Hoffman	210/761 X
3,920,506	11/1975	Morgan	210/761 X
4,000,068	12/1976	Nelson et al.	210/762 X
4,013,560	3/1977	Pradt	210/761 X
4,141,829	2/1979	Thiel et al.	210/762

OTHER PUBLICATIONS

Wightman, "Studies in Supercritical Wet Air Oxidation", Master's Thesis, University of California, Berkeley, Mar. 1981.

Primary Examiner—Thomas G. Wyse

[57] **ABSTRACT**

Organic materials are oxidized in supercritical water to obtain useful energy and/or resultant materials. In one embodiment, conventional fuels are oxidized with high efficiency to obtain useful energy for power generation and/or process heat. In another embodiment toxic or waste materials are converted to useful energy for power and heat and/or to non-toxic resultant materials. The method is also useful to permit use of a wide range of organic materials as a fuel in the desalination of seawater and brine or the removal of certain inorganic salts from water.

29 Claims, 5 Drawing Figures

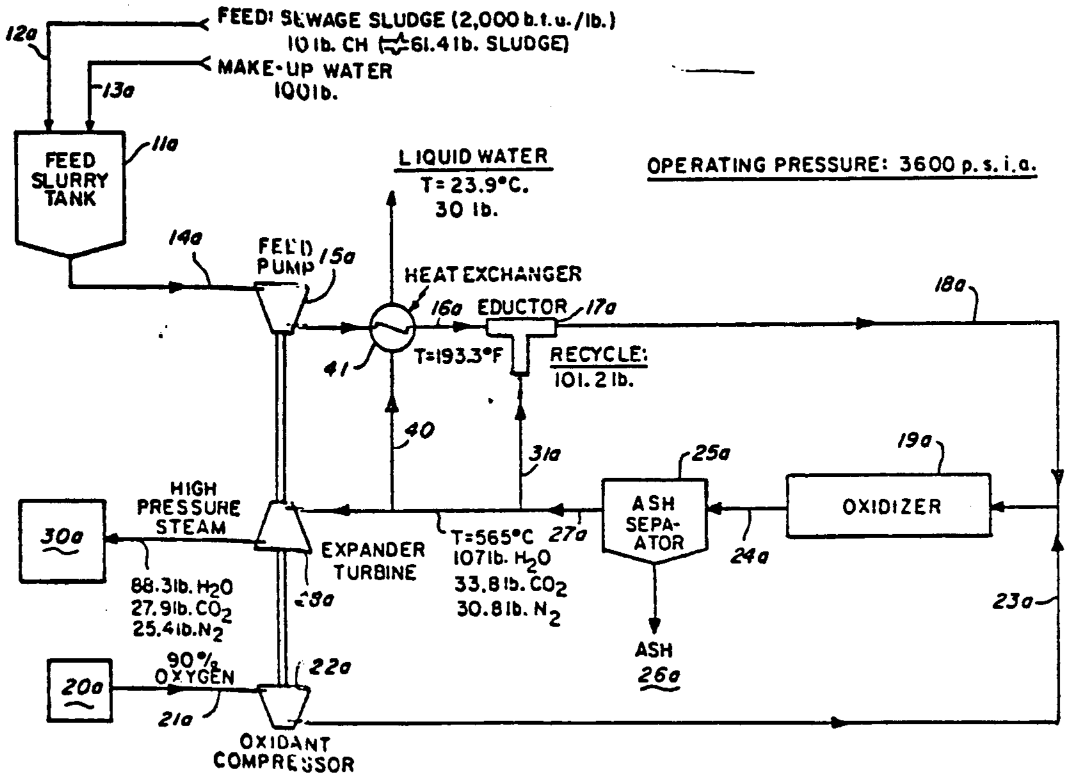


Fig. 1

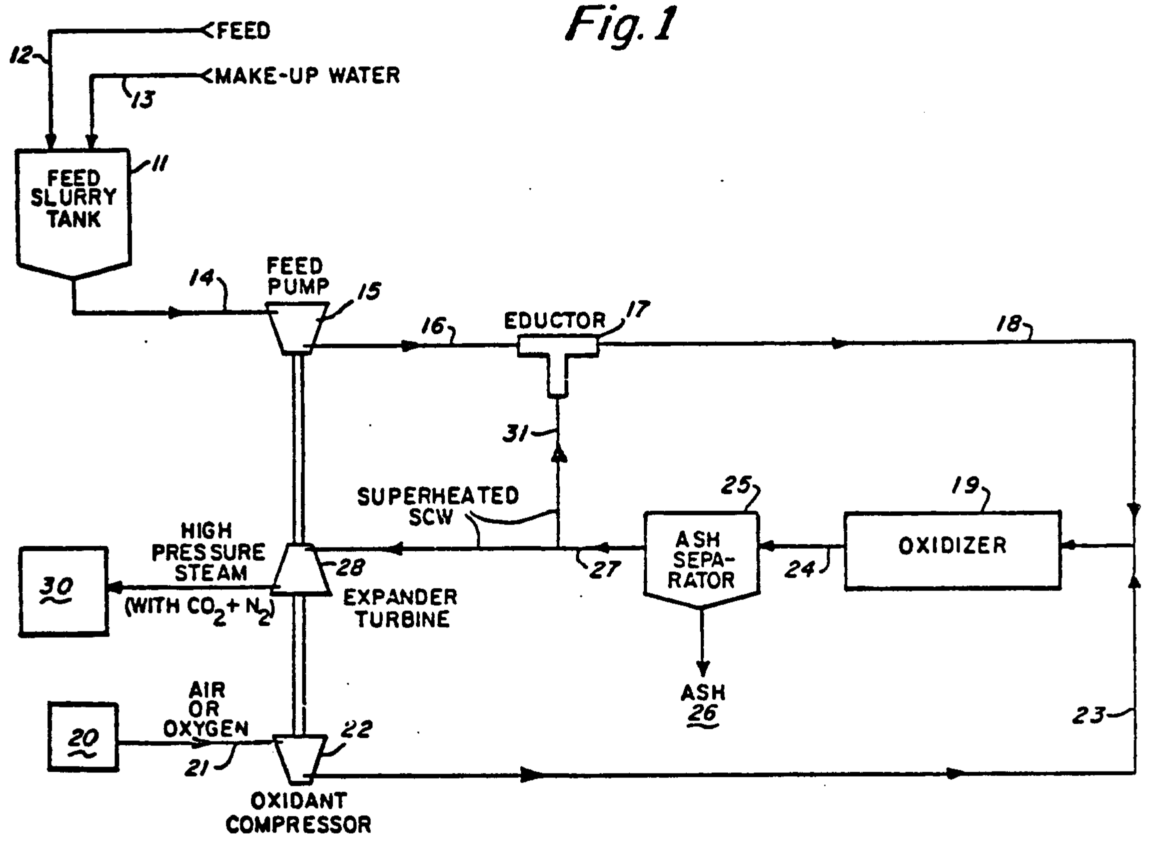

FEED
MAKE-UP WATER
12
13
FEED SLURRY TANK
11
14
FEED PUMP
15
16
EDUCTOR
17
18
31
SUPERHEATED SCW
25
19
HIGH PRESSURE STEAM
(WITH CO_2 + N_2)
28
EXPANDER TURBINE
27
ASH SEPARATOR
24
OXIDIZER
30
ASH
26
AIR OR OXYGEN
20
21
22
23
OXIDANT COMPRESSOR

Fig. 1A

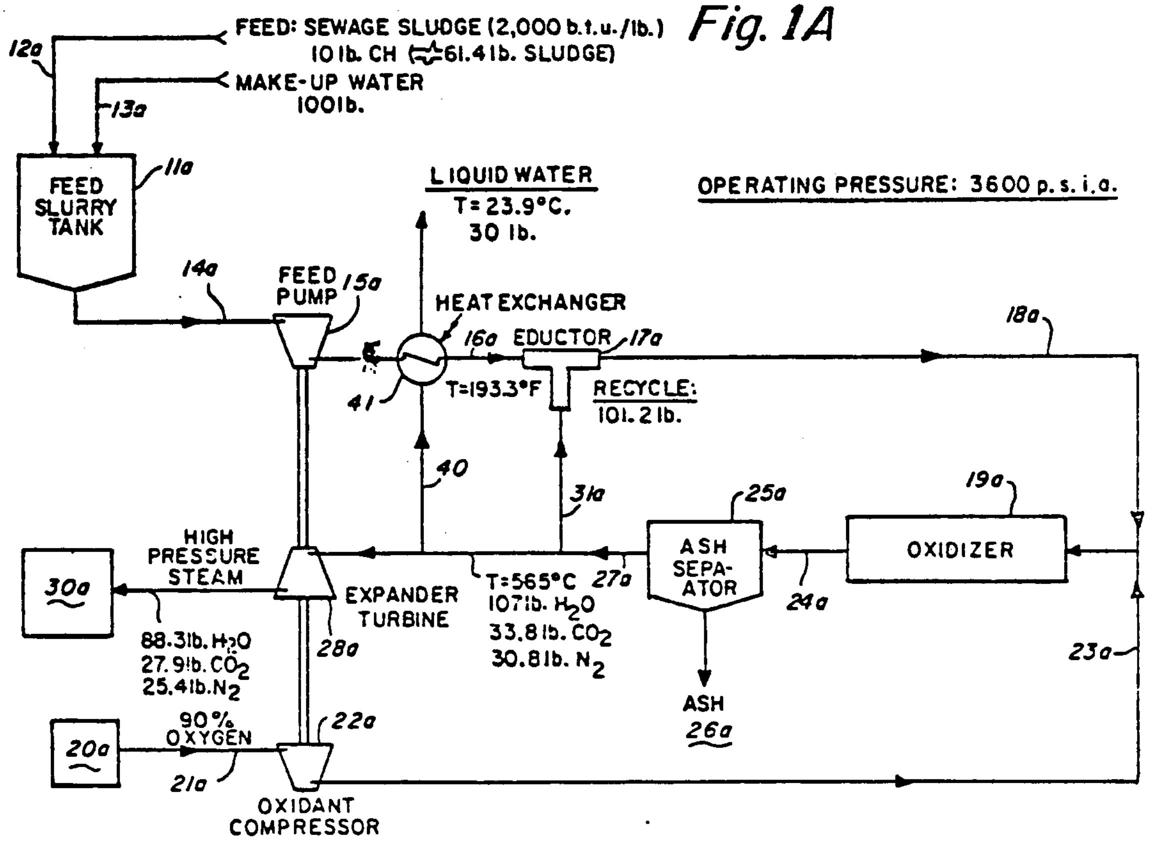
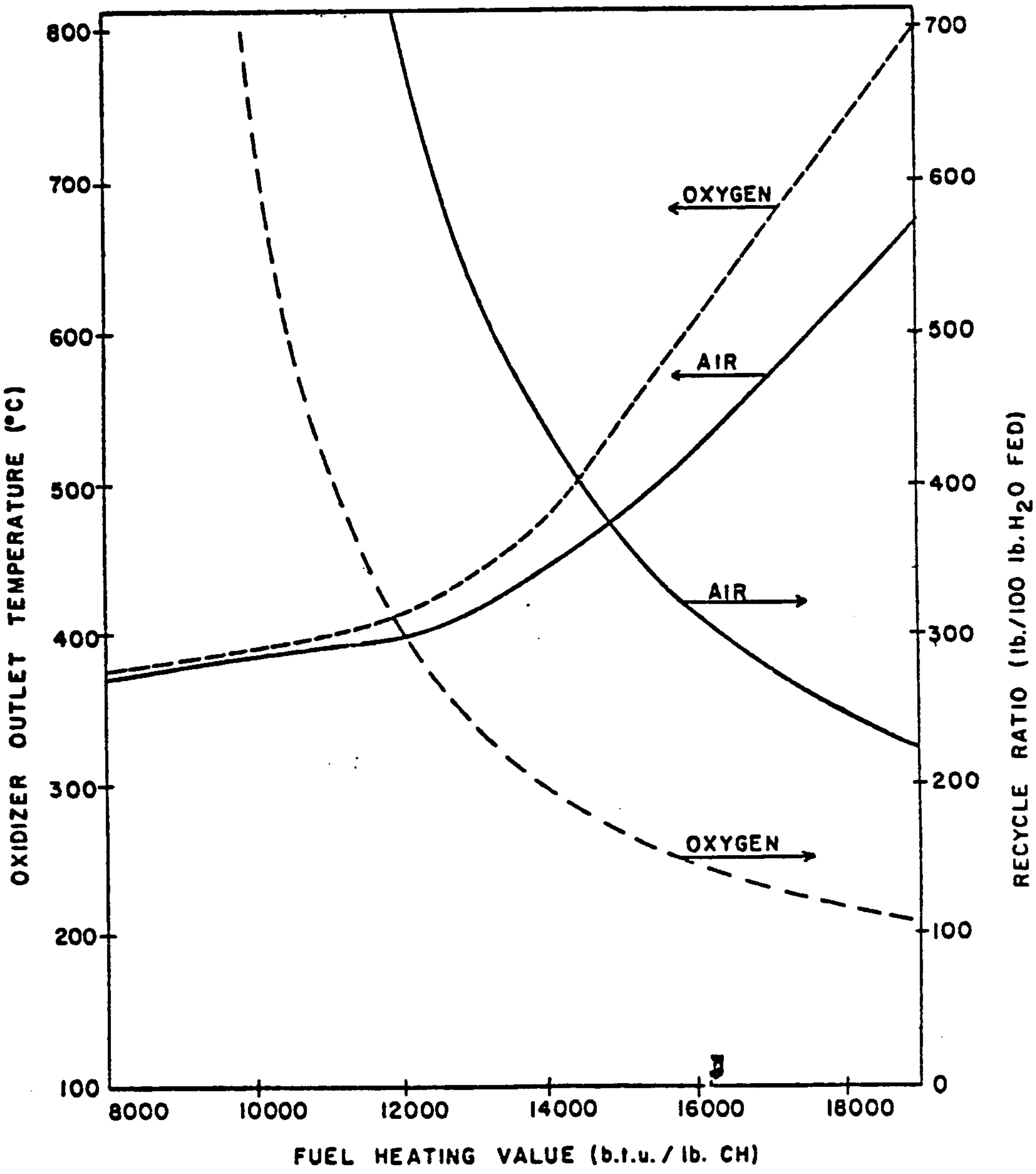
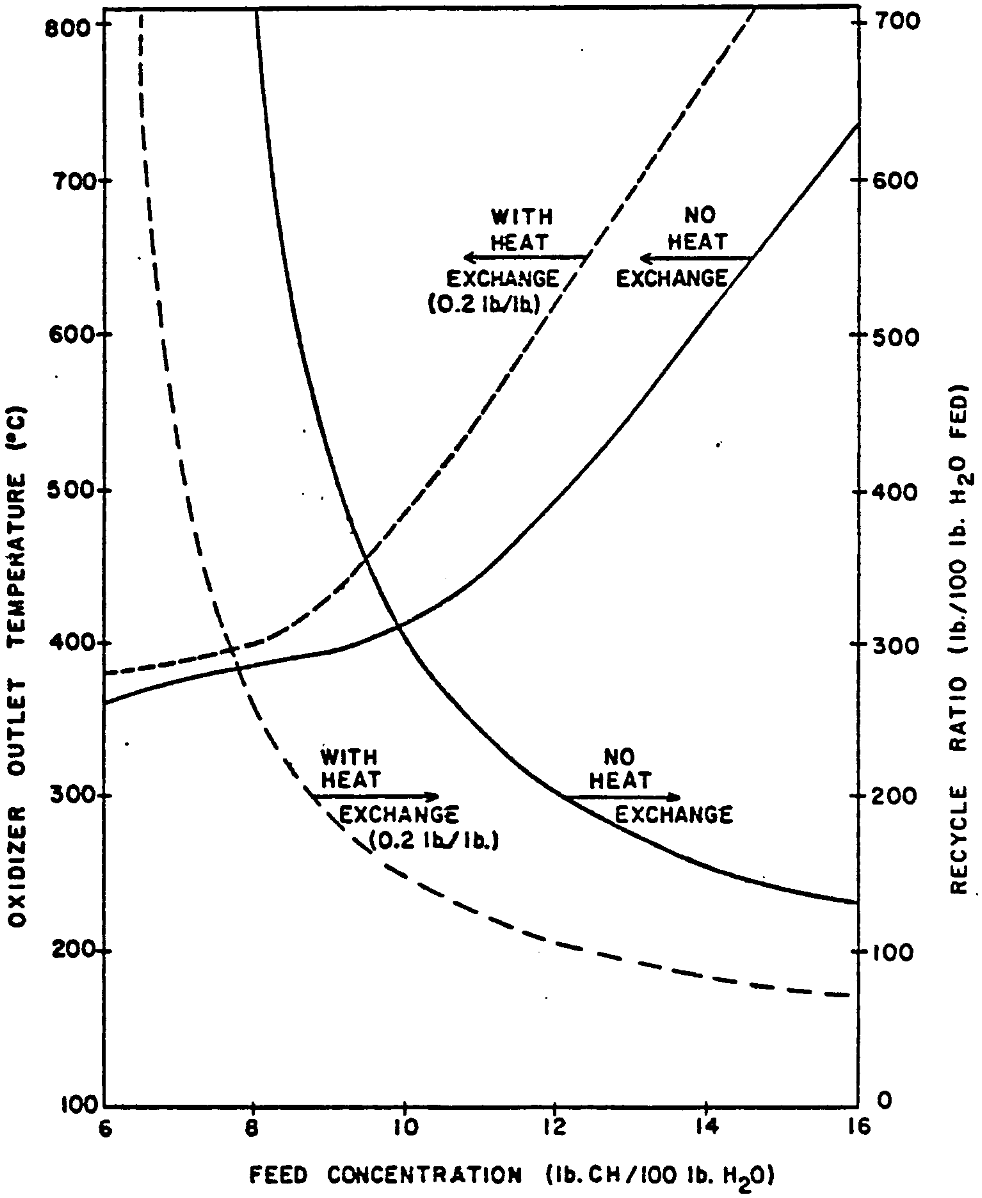

FEED: SEWAGE SLUDGE (2,000 b.t.u./lb.)
10 lb. CH (≈61.4 lb. SLUDGE)
MAKE-UP WATER
100 lb.
12a
13a
FEED SLURRY TANK
11a
LIQUID WATER
T=23.9°C.
30 lb.
OPERATING PRESSURE: 3600 p.s.i.a.
14a
FEED PUMP
15a
HEAT EXCHANGER
16a
EDUCTOR
17a
18a
41
T=193.3°F
RECYCLE:
101.2 lb.
40
31a
25a
19a
HIGH PRESSURE STEAM
ASH SEPARATOR
OXIDIZER
30a
EXPANDER TURBINE
T=565°C
27a
107 lb. H_2O
33.8 lb. CO_2
30.8 lb. N_2
24a
88.3 lb. H_2O
27.9 lb. CO_2
25.4 lb. N_2
28a
23a
ASH
26a
90% OXYGEN
22a
20a
21a
OXIDANT COMPRESSOR

Fig. 2



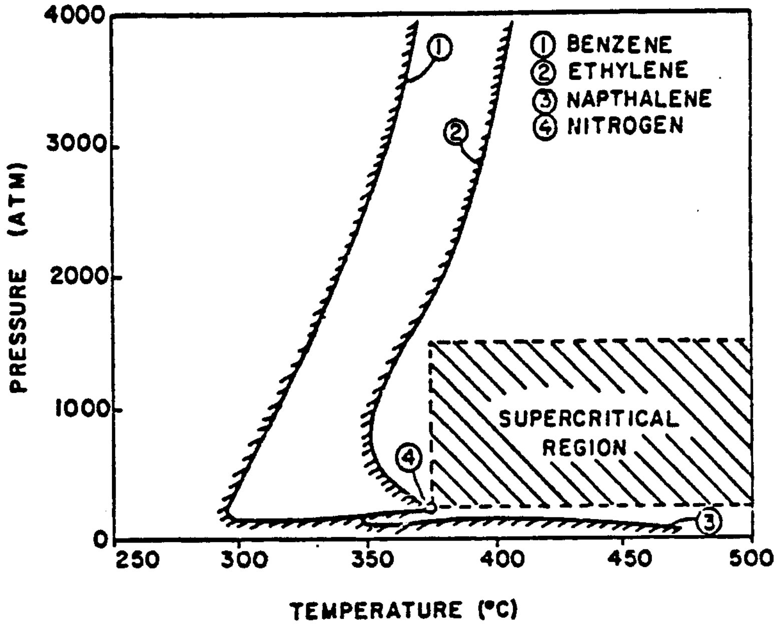
THE EFFECT OF FUEL HEATING VALUE ON OXIDIZER OUTLET TEMPERATURE AND RECYCLE RATIO. (FUEL CONE: 10 lb. CH / 100 lb. H_2O; OPERATING PRESSURE: 3600 p.s.i.a.; NO HEAT EXCHANGER; OXIDIZER INLET TEMPERATURE: 377° C.)

Fig. 3



THE EFFECT OF FEED CONCENTRATION ON OXIDIZER OUTLET TEMPERATURE AND RECYCLE RATIO. (FUEL HEATING VALUE: 12000 b.t.u./lb. CH; OXIDANT: PURE OXYGEN; OPERATING PRESSURE: 3,600 p.s.i.a.)

Fig. 4


4000
3000
2000
1000
0
PRESSURE (ATM)
250
300
350
400
450
500
TEMPERATURE (°C)
① BENZENE
② ETHYLENE
③ NAPTHALENE
④ NITROGEN
①
②
③
④
SUPERCRITICAL REGION

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 4,338,199
DATED : July 6, 1982
INVENTOR(S) : Michael Modell

It is certified that error appears in the above—identified patent and that said Letters Patent is hereby corrected as shown below:

Column 9, line 3, after "Cu_3O_4" insert --AgO--.

Column 9, line 10, change "ar" to --are--.

Column 12, line 18, change "oxidizder" to --oxidizer--.

Column 13, line 26, change "oxidiation" to --oxidation--.

Signed and Sealed this

Seventh Day of *September 1982*

[SEAL]

Attest:

GERALD J. MOSSINGHOFF

Attesting Officer *Commissioner of Patents and Trademarks*

PROCESSING METHODS FOR THE OXIDATION OF ORGANICS IN SUPERCRITICAL WATER

BACKGROUND OF THE INVENTION

The oxidation of organic materials to carbon dioxide and water is a process known almost since the beginning of time and often used to dispose of waste materials and/or generate useful energy such as steam for heating, power generation and in some cases, for desalination of seawater. In conventional generation of energy in the form of steam often organic fuels are oxidized rapidly in combustion to produce heat which is then transferred through a heat exchanger to a fluid such as water. There are inherent losses in this conventional system. For example often 10 to 15% of the heating value of the fuel is necessarily lost in the exhaust stack of conventional boilers. In addition, the heat exchangers necessarily add to cost and expense and are often of relatively large size. Heat transfer through surfaces of heat exchangers sometimes causes problems and often requires the use of specialized materials when high temperatures are involved. Hot spots due to salt deposition on boiler tubes can cause expensive down-time due to rupture of tube walls. On the flame or hot gas sides of the tubes, ash or other deposits often impede heat flow and reduce heat transfer efficiency.

In one known process for treating waste organic materials, i.e. the wet air oxidation process, an organic feed and oxidizing agent are pressurized to reaction conditions of from about 1500 to 2500 psia, heated to operating temperature and fed to a reactor for residence times of 0.5 to 1 hour. This process is known to be effective for removing 70–95% of the initial organic material. This system is effective but has certain disadvantages. It is often costly in that large size equipment is necessary and inefficient recovery of the heat of combustion is obtained. Often the solubility of oxygen or air in water is below the level required for complete oxidation of the organic materials. Thus, a two-phase water-gas mixture is often used in the reactor, necessitating provisions for agitation in the reactor so as to avoid excessive mass transfer resistance between the phases. This tends to make the reactor somewhat complicated and more expensive than would otherwise be necessary. Often volatile organics such as acetic acid remain after complete processing. Long residence times are needed and the reactions are often not adiabatic which results in loss of part of the heat of combustion to the environment. When energy is recovered in the form of steam, the temperature of the steam produced is below that of the reactor effluent, which is usually below 300° C. and typically in the range of 250° C. Thus, the heat recovered is of a low to moderate value and significantly below that required for generating electrical power in modern steam cycle power plants.

It has been suggested to recover heat energy from supercritical water effluent and the technology for doing this is highly developed. Electrical utilities since the 50's have used supercritical water power cycles to generate power from fossil fuels.

The known literature describes production of supercritical water by burning fossil fuels followed by the use of equipment for recovering heat from the supercritical water and turning the heat into power. Thus, such recovery systems are known. Rankine cycle type equipment can be used to recover useful energy from water at supercritical conditions and temperatures above 450° C. as known in the art.

It has been suggested that toxic organic materials can be reformed at the supercritical conditions of water to harmless lower molecular weight materials by breakdown of organic chains and the like whereby the resulting non-toxic materials can be disposed of by conventional means.

SUMMARY OF THE INVENTION

It is an object of this invention to provide a method of oxidizing organic materials to obtain useful energy and/or detoxify or destroy noxious and toxic organic materials and/or remove unwanted salts from water.

It is another object of this invention to provide a method in accordance with the preceding object which enables oxidizing of conventional and unconventional organic fuels efficiently with maximized energy recovery in simplified apparatus for use in a wide variety of heating and power cycles.

It is still another object of this invention to provide means and methods for rendering harmless and/or easily disposable, waste and/or toxic organic materials where the energy of oxidation thereof can be harnessed to carry out the processing and in some cases useful excess energy is produced.

It is still another object to provide a method in accordance with the preceding objects which can be used to desalinate seawater and brine using the energy of the organic material and in some cases while obtaining additional useful energy and/or treating waste or toxic materials.

It is still another object of this invention to provide methods in accordance with the preceding methods which can be carried out in simplified equipment at high reaction rates.

It is still another object of this invention to provide apparatus for carrying out the methods of this invention.

According to the invention organic materials are oxidized in an oxidizer by forming a reaction mixture of the organic materials, water and oxygen with the reaction mixture preferably at supercritical conditions. The mixture is reacted in a single fluid phase in a well-insulated reactor to cause the organic material to be oxidized whereby the effluent stream picks up the heat generated. The organic material can be waste and/or toxic material which are merely oxidized and destroyed in the method. The organic material can be a waste, toxic material or other organic material useful as a fuel and is oxidized to recover useful energy for heating or to obtain a mixture of supercritical water and carbon dioxide suitable for use as process water in power cycles.

In another preferred method, the organic material can be any organic material having sufficient heat value to raise the temperature in an oxidizer at supercritical conditions to a value of at least 450° C. The water contains a salt such as sodium chloride when the water is seawater or brine and the salt precipitates out of the single fluid phase solution immediately after reaction, as in conventional precipitating equipment, to enable desalting of the water in a rapid and continuous process.

Preferably a part of the heated water obtained which is preferably at supercritical conditions is mixed directly with the reactants which enter the oxidizer to quickly bring the reaction mixture to the desired temperature for starting the oxidation. The heated water obtained can also be used to provide heat to the reaction mixture through a heat exchange wall surface. Direct mixing is preferred since it enables reaching the desired hot temperatures rapidly, i.e. substantially instantaneously and thus avoids char formation in certain embodiments.

Preferably the organic material is used in an amount of from 2 to 25% by weight of the water at a temperature of 374° C. or above and a pressure of at least 3200 psia. Oxygen is used in the form of pure oxygen, air or other gaseous mixture but in an amount preferably equal to or greater than the stoichiometric amount required for full oxidation of the organic material. The vessel used as an oxidizer is preferably well insulated and of sufficient length to provide sufficient time for essentially complete oxidation of the organics which is preferably designed to occur in about five minutes or less.

It is a feature of this invention that substantially complete oxidation of organics using supercritical water can be carried out at high speed in relatively uncomplicated equipment. At supercritical water conditions, oxygen and nitrogen should be completely miscible with water in all proportions [see, e.g., H. A. Pray, et al., *Ind. Eng. Chem.*, 44 (5), 1146–51 (1952).]. Thus two-phase flow of gases and water are eliminated and single fluid phase flow results which allows simplification of the reactor construction often without the need for mechanical mixing. When the feed is at 374° C. prior to the onset of oxidation, the heat released by oxidation elevates the temperature of the water-organic-oxygen stream appreciably and it can easily reach 450°–700° C. If the mean temperature in the oxidizer is 400° C. or above then the residence time in the oxidizer can be less than 5 minutes. Since the oxidation occurs within a water phase, dirty fuels can be used without the need for off gas scrubbing. For example sulfur in the fuels can be oxidized to solid sulfate which would be readily recovered from the effluent stream from the oxidizer. It is part of the invention to precipitate inorganics in the feed as from a waste slurry, since the solubility of inorganic salts in supercritical water drops to very low levels as for example 1 ppb to 100 ppm above 450° C. to 500° C. The effluent from the oxidizer can easily be designed to be above 450°–500° C. thus causing inorganics in the stream to precipitate and be readily removed as by cyclones, settling columns or filters. Thus the water output from the system is purified of inorganic salts. In addition, the feed water need not be purified prior to use allowing the use of brine or seawater without prior treatment. Thus the system is ideal for shipboard use where power and/or desalted water can be obtained, sometimes simultaneously. The heat of oxidation of the organics in the feed is recovered directly in the form of high temperature, high pressure water, that is, superheated supercritical water or steam without the need for heat transfer surfaces.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objects, features and advantages of the present invention will be better understood from a reading of the following specification in conjunction with the attached drawings in which:

FIG. 1 is a schematic diagram of an apparatus useful for carrying out the process of the present invention;

FIG. 1A is a schematic diagram of an alternate embodiment thereof;

FIG. 2 is a diagrammatic showing of the effect of fuel heating value on oxidizer outlet temperature and recycle ratio;

FIG. 3 is a diagrammatic showing of the effect of feed concentration on oxidizer outlet temperature and recycle ratios; and

FIG. 4 is a diagrammatic showing of the critical locii of water mixtures.

BRIEF DESCRIPTION OF PREFERRED EMBODIMENTS

With reference now to FIG. 1 of the drawing, a schematic diagram of an apparatus for carrying out the method of this invention is shown. The organic material feed is added to feed slurry tank 11 through line 12 along with makeup water passed through line 13.

From the slurry tank, the water and organic materials are passed through line 14, feed pump 15, line 16 to an eductor 17 and line 18 into an oxidizer 19. Air or oxygen from a source 20 passes through line 21 and an oxidant compressor 22 through line 23 either directly to the oxidizer or to line 18 intermixing with the organic material and makeup water to form a reaction mixture entering the oxidizer. After the reaction in the oxidizer, an effluent stream from the oxidizer passes through line 24 to a conventional ash separator 25 where ash and inorganic salts can be removed at the bottom 26 as known in the art with the effluent stream passing through line 27 to an expander turbine 28 and out as useful energy in the form of high pressure steam or water in output 30. A portion of the effluent stream containing carbon dioxide, nitrogen if air is used as the oxidant and supercritical water at superheated temperature, that is, above the critical temperature of water 374° C. can be recycled and passed through line 31 and the eductor 17 to give the required degree of heat to the entering reaction mixture at the oxidizer.

The organic material useful as the feed of the present invention can be substantially any organic materials including fuels and waste shown on Table I below:

TABLE I

Fuel Material	Ultimate Analysis (dry wt basis) C	H	O	N	S	Ash	Btu/ lb	Btu/ lb CH
Utah coal	77.9	6.0	9.9	1.5	0.6	4.1	14,170	16,889
Pittsburgh coal #1	75.5	5.0	4.9	1.2	3.1	10.3	13,650	16,957
Pittsburgh coal #2	73.3	5.3	10.2	0.7	2.8	7.6	13,097	16,663
Wyoming coal	70.0	4.3	20.2	0.7	1.0	13.8	14,410	19,394
Douglas fir bark	56.2	5.9	36.7	0.0	0.0	1.2	9,500	15,298
Wood	52.0	6.3	40.5	0.1	0.0	1.0	9,000	15,437
Pine bark	52.3	5.8	38.8	0.2	0.0	2.9	8,780	15,112
Bagasse	47.3	6.1	35.3	0.0	0.0	11.3	9,140	17,116
Raw Sewage	45.5	6.8	25.8	2.4	0.5	19.0	7,080	13,537
Bovine waste	42.7	5.5	31.3	2.4	0.3	17.8	7,380	15,311
Rice hulls	38.5	5.7	39.8	0.5	0.0	15.5	6,610	14,955
Rice straw	39.2	5.1	35.8	0.6	0.1	19.2	6,540	14,763

TABLE I-continued

Fuel Material	C	H	O	N	S	Ash	Btu/ lb	Btu/ lb CH
			Ultimate Analysis (dry wt basis)					
MSW	33.9	4.6	22.4	0.7	0.4	38.0	5,645	14,662
Paper mill sludge	30.9	7.2	51.2	0.5	0.2	10.2	5,350	14,042
Sewage sludge	14.2	2.1	10.5	1.1	0.7	71.4	2,040	12,515
Lignite (N.D.)	42.4	6.7	43.3	1.7	0.7		7,210	14,684
Subbituminous B	54.6	6.4	33.8	1.0	0.4		9,420	15,443
Ethyl alcohol	52.2	13.0	34.8	—	—	—	12,780	19,601
Carbon	100.0						14,093	14,073
Methane	75.0	25.0	—	—	—	—	21,520	21,520
Propane	81.8	18.2	—	—	—	—	19,944	19,944
Hexane	83.7	16.3	—	—	—	—	19,403	19,403
Benzene	92.3	7.7					17,480	17,480
No.1 fuel oil								19,665
No.2 fuel oil								19,408
No.4 fuel oil								19,213
No.5 fuel oil								19,015
No.6 fuel oil				without limitation				18,794

Organic material feeds include without limitation known toxic and waste materials such as:

- Aldrin
- Dieldrin
- DDT
- 2,4,5-T and esters
- 2,4-diaminotoluene
- Lindane
- p-aminobenzoic acid
- anthranilic acid
- Alfatoxin
- Heptachlor
- Malathion
- Nitrosamines
- commuted paper waste
- landfill garbage and the like.

Organic toxic material to be treated in this invention include those recognized as hazardous by the United States Environmental Protection Agency as for example those set out in EPA publication EPA-560/1179-001 entitled Test Data Development Standards: Chronic Health Effects Toxic Substances Control Act; Section 4. When toxic and waste materials are used, it sometimes is only desired to utilize the heat of oxidation to aid in oxidizing of these materials to harmless products which can be taken off the oxidizer and discarded. The resultant supercritical water can be passed to other areas without removing the energy therefrom for use in power cycles. When moderate to high heating value input materials are used, useful energy is obtained which can be converted to power using steam turbines, Rankine/cycle systems and the like as known in the art. The heated water output can be used directly in heat exchangers for space heating or any heating purpose. Preferably the concentration of the organic materials is in the 2-25% by weight range of the reaction mixture. The partial list of possible feed materials in Table I shows that the heating value in BTU per pound of fuel varies over a broad range from 2,040 BTU/lb. for sewerage sludge to 21,520 BUT/lb. for methane. The last column in Table I is the heating value in BTU per pound of carbon and hydrogen in the fuel. On this basis, the heating values vary over a much smaller range: 12,500 BTU/lb. CH for sewerage sludge and 15,000 BTU/lb. CH for wood and bark, 16-19,000 BTU/lb. CH for coals and 18-20,000 BTU/lb. CH for fuel oils.

The heating value of the fuel defines the feed concentration and recycle ratio required to reach a given oxidizer outlet temperature. At a given fuel feed concentration the outlet temperature varies with the fuel heating value. The effect of fuel heating value on oxidizer outlet temperature and recycle ratio is shown in FIG. 2. The results of FIG. 2 were determined by the thermodynamic first law energy balance assuming negligible energy losses to the environment (Fuel conc: 10 lb. CH/100 lb. H_2O; operating pressure: 3,600 psia; no heat exchanger; oxidizer inlet temperature 377° C.). With air as oxidant, the oxidizer outlet temperature varies from 441° C. at 14,000 BTU/lb. CH to 563° C. at 19,000 BTU/lb. CH. If oxygen is used instead of air, the outlet temperature is somewhat higher as shown by the dash line in FIG. 2. The recycle ratio is determined by the oxidizer outlet temperature and the desired oxidizer inlet temperature. For an oxidizer inlet temperature of 377° C. the relationship between recycle ratio and fuel heating value is shown in FIG. 2 for air (solid curve) and oxygen (dash curve). Higher recycle ratios are required when air is used instead of oxygen because the inert nitrogen component of air decreases the oxidizer outlet temperature.

Basically higher temperatures are preferred at the outlet of the oxidizer so that a smaller proportion of water need be recycled to provide heat for the reaction. The outlet temperature will preferably always be above 374° C. when single phase reactions occur and preferably it is above 450° C. to maximize salt precipitation and to minimize the recycle. Thus with low heating value fuels, higher feed concentration reaction mixtures are used. In some cases, supplemental system heat exchangers are used along with the recycle to achieve the desired temperature at the inlet to the oxidizer.

The reaction often preferably is carried out at the near critical density of water which means that the temperature must be at least the critical temperature and the pressure at least the critical pressure of water. Parameters at the near critical condition of water can also be used and should be considered the equivalent of exact critical condition. The near critical region or the term "in the region of the critical density of water" is encompassed by densities of from 0.2 to 0.7 grams per centimeter^3. In this near critical region or in the region of the critical density, pressures can be from 200 to 2500 atmospheres and temperatures can be from 360° C. to at least 450° C. A critical temperature range of 374° C. to 450° C. and a critical density range of 0.25 to 0.55 grams per centimeter^3 are preferred for use.

Although it is preferred to have the effluent stream from the oxidizer reach a temperature and pressure condition at the near critical condition of water this can vary in some cases. In all cases the reaction in the reaction vessel or oxidizer at some point reaches supercritical conditions, i.e. temperature and pressure conditions are such that only a single homogeneous fluid phase can exist in the mixture of reactants. FIG. 4 is a graph of pressure versus temperature showing the supercritical region, i.e., the locus of critical points for binary mixtures of water with benzene, ethylene, naphthalene and nitrogen. In all cases with the mixture used for the reactants supercritical conditions are to the right and above the locus graphed. Since oxygen water mixtures have a locus similar to the nitrogen water mixture, it will be understood that temperatures and pressures to the right of line (4) should be obtained in the oxidizer. These conditions are close to the supercritical conditions of water alone. These supercritical conditions must occur in the oxidizer to get the single fluid phase reaction to permit full and rapid oxidation. In FIG. 4 the concentration of the organic in admixture with water increases as the lines go out from the water point at the lower right-hand corner of the water supercritical region shown on the graph.

The temperature and pressure going into the oxidizer can vary. The kindling temperature of the reaction mixture must be reached prior to entrance and supercritical conditions for the reaction mixture must occur at some point in the oxidizer due to the heat released in the adiabatic oxidation of a portion of the organic feed.

The initial temperature going into the oxidizer for materials that tend to char, i.e., pyrolyze or decompose, is preferably above the char formation temperature range. For example cellulosic materials tend to pyrolyze in the range of 150° C. to 325° C., so they are rapidly brought to 374° C. before the oxidizer by recycling supercritical water from the oxidizer effluent, directly therewith thus raising the temperature of the reaction mixture substantially instantaneously and minimizing char formation. On the other hand, many liquid hydrocarbon fuels do not substantially pyrolyze below 374° C. and thus can be passed in a water, oxygen reaction mixture to the oxidizer at lower temperatures as for example at least 200° C. at 220 atmospheres. Similarly many toxic materials and wastes which are liquid or solids can enter the oxidizer under the same conditions as liquid hydrocarbon fuels. Cellulosic materials preferably enter the oxidizer at at least 350° C. and 220 atmospheres. The recycle of water from the oxidizer is used to raise the reaction mixture temperature with the amount of recycle determined by the oxidizer entrance temperature desired.

All heating is preferably obtained by recycling through line 31 using the heated water and preferably supercritical water obtained from the oxidizer. The process is continuous after startup and initial heat can be obtained from an outside source for startup.

The organics in the feed can be converted to combustible compounds such as furans, furfurals, alcohols and aldehydes by the use of a reformer in line 18 if desired so that the feed passes therethrough before mixture with air or oxygen and passage to the oxidizer. The use of a reformer to gasify organic materials under supercritical conditions is known in the art and described in U.S. Pat. No. 4,113,446 issued Sept. 12, 1978 relating to gasification processes using supercritical water. Reformers as described therein can be used in the present system if desired although in most cases, they are unnecessary.

The feed material can be in liquid form as with liquid organics, aqueous slurry form, gaseous form or solid form. When in solid form, the feed is preferably comminuted for convenience for incorporation into the feed water as a pumpable slurry.

It is a feature of this invention that inorganic materials such as salts which are highly soluble in water often lose solubility and become substantially insoluble at temperatures above 450° C. Thus, when seawater, brine or other impure waters are used as makeup water, the organic materials can provide the fuel for desalting. Thus when the exit temperature from the oxidizer is above 450° C., conventional ash separators can be used to allow precipitation of sodium chloride, calcium chloride, ferric oxide and the like. These materials often cause problems in conventional apparatus where heat transfer is through walls of the apparatus. They tend to build up on the walls causing hot spots with subsequent destruction of the walls. In the present method, the oxidizer is a flow through oxidizer and can be for example a stainless steel tube covered by layers of insulation such as Min-K. When temperatures in excess of 450° C. are generated within the oxidizer or when high concentrations of chloride are present, the inner wall of the reactor may be clad with corrosion-resistant alloys such as Hastelloy C. When large diameter reactors are employed, the inner wall may be lined with firebrick. When high concentrations of inorganic constituents are present or when solid catalysts are used to reduce the residence time required for oxidation, a fluidized bed reactor can be used to provide efficient separation of fluid effluent from solids.

The superheated supercritical water in line 27 is passed for recycling to provide the heat necessary at the starting point in the oxidizer or through the expander turbine to form the high pressure steam useful in a conventional power cycle such as 30. Diagrammatic box 30 represents a heat user component. This can be a heat exchanger where the process heat generated is used for space heating or for obtaining useful energy in any known conversion apparatus.

The oxidizer allows single phase reaction which is extremely important to minimize the cost, expense and complexity of the oxidizer itself and maximize rapid reaction in time periods of less than one to 5 min.

The supercritical water process of this invention for generating high pressure steam has several advantages over conventional processes that are used for the same purpose. The feed organic material even if wet forest products, can be used directly without drying because water is used as the carrier fluid for both oxidation and reforming when reforming is first carried out. Oxidation takes place rapidly and yet under safe, controlled conditions. Auxillary equipment for pollution control is not necessary because the oxidation products are maintained within a close continuous system. Supercritical steam can be generated without problems associated with heat transfer through surfaces thus minimizing costs and equipment failures. High thermodynamic efficiencies can be obtained with supercritical steam since there is no stack heat loss.

Because a homogeneous single phase mixture of organics, oxidant and water is used, complete oxidation of the organics is facilitated and simplified reactors can be used. A simple tube, or fluidized bed can be used which contain no moving parts. Oxidation catalysts if used, can be those of common metal oxide or supported metal catalysts which provide sufficient activity for oxidation such as Fe_3O_4, MnO_2 and CuO, NiO, Al_2O_3, Cu_3O_4, Pt or Pt. In some cases, inorganic components of the feed which are normally present in water from artificial sources such as the sea or inorganic components of fossil fuels or wood products provide sufficient catalytic activity for rapid reactions. The oxidation process is so fast that the reactor often approaches adiabatic operation, that is, heat losses from the oxidizer ar negligible and the oxidizer effluent contains essentially all of the enthalpy of oxidation. Thus the outlet temperature of the oxidizer is determined by the concentration of the organics in the feed and their heating value.

In a first illustrative example, illustrating the invention and using the system of FIG. 1, the feed can be fuel oil having a heating value of 19,000 BTU/lb. with 8.7 pounds added to the feed slurry tank 11 along with 100 pounds of makeup water. This material is mixed and makeup water provided to a concentration of 5 to 20% by weight of the organic material with 8.7 weight % CH in one embodiment. The mixture is pressurized to a supercritical pressure above 3200 psia with 3600 psia in one embodiment and heated to a temperature in the vicinity of the critical temperature of water, e.g., 377° C. The preheating of FIG. 1 is accomplished by directly injecting a portion of the oxidizer effluent through line 31. In some cases, a heat exchanger can be used instead of direct injection of water to recycle heat derived from the flow coming from the oxidizer. In other cases, the feed material and makeup water can be heated although this is not preferred. Air or oxygen is pressurized and mixed with the pressurized fuel water mixture at 3600 psi with the proportion of oxygen adjusted to be equal to that required to completely oxidize the feed fuel, that is, at least stoichiometric. The temperature of the mixture of fuel, oxidant and water at the entrance to the oxidizer is above the kindling temperature required for the components of the fuel that are most readily oxidized. If no catalyst is used the kindling temperature can be as high as 350° to 400° C. but if catalysts are used the kindling temperature may be as low as 200° to 250° C.

The mixture of reactants is fed to the oxidizer 19 which can be a tubular reactor or fluidized bed. Low length-to-diameter (L-D) ratios in the fluidized bed are desired where the inorganic content is high so as to minimize the oxidizer reactor surface area and thereby minimize deposition of inorganics on the walls of the reactor. The reactor operates adiabatically and the heat released by oxidation of readily oxidized components is sufficient to raise the fluid phase to temperatures above the critical temperature of the mixture. At that point the fluid becomes a single, homogeneous phase. For 8.7 weight % of fuel oil in the feed, with air as the oxidant, the heat of oxidation is sufficient to raise the oxidizer outlet temperature to 565° C.

The effluent from the oxidizer is fed to the ash separator 25 where inorganics originally present in the feed and/or water are removed. The ash separator can be a cyclone, a settling column or any suitable solid-fluid separator.

A portion of the superheated supercritical water is recycled to the eductor 17 upstream of the supercritical oxidizer. This operation provides for sufficient heating of the feed to bring the oxidizer effluent to supercritical conditions. The remainder of the superheated supercritical water is available for power generation, heating or use as high pressure steam. A portion of available energy is used to generate the power required to pressurize feed and oxidant. The energy required to pressurize the oxidant is recovered in the expansion of the products of oxidation in the superheated supercritical water turbine. In this example, the temperature at the inlet of the oxidizer 19 is 377° C., 258 pounds of water are recycled through line 31 with the outlet in line 24 being at a temperature above the critical conditions of water and having a temperature of 565° C. for 106 pounds water, 29 pounds of carbon dioxide and 105 pounds of nitrogen.

This method of oxidation is analogous to that of a turbojet or gas turbine. The process illustrated does not require heat transfer through surfaces as in conventional fuel oil boilers. This is a major advantage resulting from the invention. In the conventional processes for generating supercritical steam, boiler feed water must be extremely pure to minimize deposition and buildup of inorganics on the water side of the boiler tubes. The direct oxidation of fuels or other organics in water avoids this problem completely and thus allows one to take full advantage of the high thermodynamic efficiency of generating power with supercritical steam. In fact it is possible to use impure water such as brine or seawater as feed because the inorganic salts are removed in the ash separator. The high temperature, high pressure steam produced by the process can thus be used as a source of desalinated water after condensation and removal of carbon dioxide and nitrogen if air is used as the oxidant.

In a second example using the system of FIG. 1, Douglas fir bark is processed in steps similar to those described above in the first example. The heating value of the Douglas fir bark (9,500 BTU/lb.) is considerably less that that of fuel oil. Therefore a higher weight fraction of feed (11.6 lbs. CH) 16.1 pounds bark to 100 pounds of water is required to reach the same oxidizer effluent temperature of 565° C. Since the recycle ratio is determined by the energy required to bring the feed to the desired oxidizer inlet temperature, an increase in feed concentration results in an increase in recycle ratio. Thus 298 pounds of oxidizer effluent per 100 pounds of water feed must be recycled with bark feed whereas about 259 pounds is recycled when fuel oil is the feed.

In the second example, the temperature in line 27 is 565° C., 100 pounds of water in the line contains 39.2 pounds of carbon dioxide and 141 pounds of nitrogen. The inlet temperature to the oxidizer is 377° C. and the operating pressure is 3600 psia when 11.6 pounds CH that is 16.1 pounds bark of Douglas fir (9,500 BTU/lbs.) is used with oxygen. Bark and the like when used in this invention is comminuted into particles preferably having a size of about ½ mm or less.

The process illustrated in FIG. 1 when used for generating high pressure stream from forest product wastes has several advantages over conventional processes that are used for the same purpose. Drying of feed is unnecessary because water is used as the carrier fluid for oxidation. Oxidation is effected rapidly and yet under safe controlled conditions. Auxiliary equipment for pollution control is not necessary because the oxidation products are maintained within the system.

In a third example a reformer (not shown) is put in the line 18 and comprises merely a tube which permits reforming of coal used as the feed. In this example 10 pounds CH of coal having a heating value of 13-14,000 BTU/lb. is admixed with 100 pounds of water, recycling 275 pounds of water from the oxidizer line 27 through the reformer. The entrance temperature to the oxidizer is 377° C. and the exit temperature is 565° C. with a mixture of 107 pounds water, 33 pounds CO_2 and 121 nitrogen when air is used as the oxidizing agent. The operating pressure of the system is 3,600 psi. The reformer provides sufficient residence time in an oxidant-free environment to allow a significant portion of the solid fuel to be solubilized. As described in U.S. Pat. No. 4,113,446 solids such as wood, coal and the like can be dissolved to an appreciable extent in water under supercritical conditions. Where such solids are to be subsequently oxidized, it may be advantageous to first dissolve them in the supercritical water phase. The effect of reforming may provide for a significantly lower kindling temperature in the oxidizer. Where the oxidation is solid catalyzed, this solution prior to catalytic oxidation can also facilitate mass transfer of fuel to the surface of the solid catalyst thereby enhancing the oxidation rate. However, in many cases, no distinct reforming step is required and the materials are solubilized in passage to the oxidizer.

In a further example showing the oxidation of sewerage sludge, a system as shown in FIG. 1 is used using sewerage sludge having a BTU output of 2,000 BTU/lb. 13.3 pounds CH (81.6 pounds sludge) is used with 100 pounds of makeup water operating at a pressure of 3600 psi with a recycle of 169.4 pounds water from the oxidizer and an input temperature of 377° C to the oxidizer. When oxygen is used as the oxidant, the temperature at the oxidizer outlet is 1050° F. with 109.3 pounds of water and 44.9 pounds of CO_2 in line 27. This system can also be used with toxic and hazardous chemicals in low amounts as in wastes, feed lot wastes, agricultural by-products, textile wastes, carpet wastes, rubber by-products, forest product wastes, paper and pulp mill wastes and the like.

Disposal by oxidation of sewerage sludge waste is representative of one of the more difficult wastes in the sense that the heating value of the sludge typically runs around 2,000 BTU/lb. of sludge. A process for oxidizing sewerage sludge as described differs from those described previously in that the oxidant is preferably relatively pure oxygen (98%). The high percentage of oxygen enables relatively lower sludge feed concentrations than if air were used.

In another example, sewerage sludge in an amount of 10 pounds CH (61.4 pounds sludge) is mixed with 100 pounds of water in a system substantially as set up with respect to FIG. 1. This example is diagrammatically illustrated in FIG. 1A where all numbered parts marked "a" are identical to corresponding numbered parts of FIG. 1. Water in an amount of 30 pounds at a temperature of 24° C. is removed from a heat exchanger 41 which receives water in the near critical region through line 40. The preheating of water in line 16*a* is necessary to get enough heat at the entrance to the oxidizer so that the entrance value is 377° C. thereby allowing single phase operation of the oxidizer. Line 27*a* has a temperature of 549° C. with 107 pounds water 33.8 pounds CO_2 and 30.8 pounds N_2 passing through the turbine after the recycle extraction to give 88.3 pounds of water 27.9 pounds CO_2 and 25.4 pounds N_2. Ninety percent oxygen is used. Thus a feed of 61 pounds sludge and 100 pounds water is preheated to 193° C. by passing 30 pounds of oxidizer effluent to the heat exchanger. The effect of indirect preheat of the feed is similar to that of increasing feed heating value or concentration. The recycle ratio necessary to reach a given oxidizer inlet temperature is decreased. At the same time, the oxidizer outlet temperature is increased because the heat of oxidation is taken up by a smaller quantity of fluid passing through the reactor.

The specific oxidizer inlet and outlet temperatures can vary as for example depending on whether oxygen or air is used in the reaction mixture, see FIG. 2.

FIG. 3 shows the effect of feed preheat with a heat exchanger 41 or without it. For a feed with 12,000 BTU/lb. heating value and pure oxygen and operating pressure of 3,600 psia the oxidizer outlet temperature and recycle ratio are shown as a function of feed concentration in solid curves. Superimposed on this figure are the corresponding values (dashed curves) when 20 pounds of oxidizer effluent (per 100 pounds of feed water) are used to preheat the feed through the heat exchanger. Higher degrees of preheat (i.e., larger proportions of oxidizder effluent to the exchanger) would lead to further increases in oxidizer outlet temperature and lower recycle ratios.

While specific examples of this invention have been shown and described, many variations are possible. The reactor can have various configurations such as tubes, cylinders or fluidized beds of austenitic steel. When corrosive components such as chlorides are present, the tubular reactors preferably are clad with corrosion-resistant alloys such as Hastelloy C. Various compressors, eductors and the like can be used.

The power output can be effected using turbines commonly manufactured for expansion of supercritical water in supercritical power cycles.

A key feature is that a single fluid phase reaction occurs in the oxidizer at supercritical conditions of the reaction mixture and preferably at the near critical condition of water. In some cases, the oxidation can start at a temperature below the critical temperature of water as at the kindling temperature of the organic material. In all cases the starting mixture and subsequent products are considered the reaction mixture. At some point in the reaction in the oxidizer the mixture reaches the supercritical condition and preferably the near critical condition of water and a temperature of at least 374° C. to give a single phase reaction enabling essentially complete oxidation by a stoichiometric amount of oxygen. The pressure used in the continuous system of this invention is preferably always in the near critical region of water and thus always at least 220 atmospheres.

Although only a single organic material has been specifically noted in each example, it should be understood that the feed material can be a mixture of organics. In some cases, the mixture of organics can be unknown or undetermined as to its exact makeup. It is only important that a sufficient concentration of organics having the required heating value be used so that when reacted with stoichiometric amounts of oxygen, the effluent stream will have a temperature such as to produce some aid in providing the heat required for bringing the feed to appropriate conditions for the oxidizing reaction. It is an important feature of the invention that the heat produced by the oxidation can be used at least in part in a portion of an effluent stream to recycle directly with the reaction mixture to provide heat thereto and/or to be passed to a heat exchanger to provide heat to the reaction mixture through a heat exchange surface. When a portion of the effluent stream from the flow through oxidizer is recycled directly into the stream as at 17 substantially instantaneous heat transfer occurs. Simple eductors and other nonmechanical agitator mixing means and methods can be used. In some cases the water and oxidation product stream from the oxidizer is used entirely as a power or heat source.

The term "single homogeneous fluid phase" as used herein has its ordinary known meaning with respect to the mixture of fluids present where the mixture is at uniform pressure, temperature, density and concentration. There is some change in all parameters except pressure in the reactor or oxidizer, however, at any cross section all parameters are substantially uniform in the single homogeneous fluid phase. Thus it is important that there is at least one portion of the reaction mixture in the oxidizer where there is no dispersion of one fluid in another.

What is claimed is:

1. A method of obtaining useful energy and oxidizing organic materials in an oxidizer, said method comprising forming a reaction mixture of said organic material, water and oxygen,

and reacting said mixture in a single homogeneous fluid phase under conditions characterized by a temperature of at least 377° C. and a pressure of at least 220 atmospheres to cause said organic materials to be oxidized thereby raising the temperature of said water and oxidiation products.

2. The method of claim 1 wherein at least a portion of the effluent from said oxidation region is connected with a power generating device.

3. A method of treating an organic material containing waste by an oxidation process, said process comprising obtaining a mixture of said waste with water, said water acting as a carrier fluid and admixing oxygen therewith to form a reaction mixture in a continuous flow and substantially completely oxidizing said organic material in a flow through reactor wherein said reaction occurs with said mixture as a single homogeneous fluid phase under conditions characterized by a temperature of at least 377° C. and a pressure of at least 220 atmospheres.

4. A method of removing inorganic salts from water, said method comprising admixing an organic material with said water carrying an inorganic salt and oxygen to form a reaction mixture, wherein said organic material comprises from 2 to 25% by weight of said water forming a single fluid phase of said reaction mixture under conditions characterized by a temperature of at least 377° C. and a pressure of at least 220 atmospheres and oxidizing said organic material to obtain a temperature of at least 450° C. in an effluent stream,

and removing said inorganic salts as particulates from a stream of reactants with the aid of the temperature elevated above 450° C. to reduce the solubility of said inorganic salts.

5. The process of claim 4 wherein said inorganic salts are soluble in water below the supercritical conditions for water.

6. The method of reacting an organic material which comprises

mixing said organic material with water and a fluid comprising oxygen to form a mixture,

causing said mixture to undergo reaction in a single substantially homogeneous fluid phase under conditions characterized by a temperature of at least 377° C. and a pressure of at least 220 atmospheres.

7. The method of claim 6 which includes the steps of:

carrying out said mixing step at a pressure supercritical for said water; and

introducing said mixture into a flow reactor.

8. The method of claim 6 in which said organic material is at least one-half percent of said mixture.

9. The method of claim 6 in which said water is at least forty percent of said mixture.

10. The method of claim 6 in which said reaction requires no more than five minutes.

11. The method of claim 6 in which said mixture includes an inorganic salt; and

said mixture is subjected to temperature sufficiently high to render insoluble said inorganic salt.

12. The method of claim 11 in which said mixture is brine and a result of said reaction is desalination of said brine.

13. The method of claim 6 which additionally includes the step of removing useful power generated by said reaction.

14. The method of claim 6 in which an undesirable organic material is changed in chemical composition in said reaction.

15. The method of claim 6 in which heat produced in said reaction is reintroduced into said reaction.

16. The method of claim 15 wherein the reintroduction of heat produced in said reaction provides the total heat energy to maintain said reaction.

17. The method of claim 15 in which a portion of effluent from said reaction is added to said mixture.

18. The method of oxidizing an organic material, which comprises the steps of forming a reaction mixture comprising the organic material, water and an oxygen-containing gas and flowing such reaction mixture through an oxidation region; causing the reaction mixture to be brought to an oxidation temperature which is at least 377° C. at a pressure of at least 220 atmospheres and which would establish for the water in the oxidation region a supercritical density which is less than about 0.7 gm/cm^3, and controlling the ratio of oxygen and organic material in the reaction mixture and the rate of flow thereof through the oxidation region so as to oxidize the organic material within the oxidation region.

19. The method of claim 6 or 18 in which said organic material is first mixed with said water to form a preliminary mixture; and

said preliminary mixture is then mixed with said fluid comprising oxygen to form said mixture.

20. The method as defined in claim 18 wherein the mean temperature of the oxidation region is at least 400° C. whereby the residence time for substantially complete oxidation is less than 5 minutes.

21. A method in accordance with the method of claim 18 wherein said organic materials are selected from the class consisting of fuels, toxic materials and waste materials, and aqueous slurries or solutions thereof.

22. The method of claim 18 wherein the effluent from the oxidation region reaches a temperature of at least 450° C., and inorganic salts are precipitated from the effluent.

23. The method of claim 18 wherein at least a portion of the effluent from the oxidation region is recycled to preheat the water entering the oxidation region.

24. The method of claim 18 wherein the effluent from the oxidation region is used to provide heat to raise the temperature and energy to raise the pressure of the reaction mixture.

25. The process of claim 18 wherein the kindling temperature for the organic material is reached prior to said oxidation region.

26. The process of claim 18 wherein the concentration of organic material is sufficient to provide the required heating value so that when reacted with stoichiometric amounts of oxygen the effluent stream will have a temperature which is adequate to provide a useful energy source.

27. The method of claim 18 wherein the effluent from the oxidation region is passed through a heat exchanger and/or added directly to said mixture to provide heat to said reaction.

28. The process of claim 18 which comprises supplying heat and pressure to said reaction mixture to provide a selected reaction pressure and a selected initial temperature in which the selected initial temperature is at least the kindling temperature of the reaction mixture and the selected reaction pressure is at least the critical pressure of water and recycling at least a portion of the supercritical effluent from the oxidation region.

29. The process of claim 18 wherein the heat value of said organic material is adequate to provide a temperature of at least 450° C. in said oxidation region.

* * * * *

APPENDIX G

The Roswell Test Facility

The Roswell Test Facility (RTF)

The RTF is owned and operated by the City of Roswell. It was conveyed to the City in 1984 by act of Congress. For more than a year prior to conveyance, the City operated the RTF through a cooperative agreement with the United States Department of the Interior. Since the City first assumed operational responsibility for the RTF, several research projects have been initiated there either by or for various public institutions and private firms, including New Mexico State University, Battelle Laboratories and the FilmTec Corporation.

Personnel presently employed at the RTF have each worked there a minimum of five years. They're individually experienced in operating desalinization equipment, conducting other testing and research, and performing chemical and microbiological analysis. Additionally, the City has a staff of four professional engineers who can consult and coordinate as necessary on tests and research projects.

The RTF contains a machine shop and laboratory, both staffed on a full time basis. The laboratory is certified by the New Mexico Environmental Improvement Division for microbiological analysis and analysis pertaining to public drinking water. It is the only commercial laboratory within 200 miles of Roswell.

The RTF also contains an office building, staffed on weekdays by a receptionist in the lobby. Fully-furnished suites, offices and conference rooms are available for lease by researchers.

Charges in effect for FY 84-85 (July 1, 1984, through June 30, 1985) are as follows:

(1) **Operating** (utilities, chemicals, parts, etc.) at direct cost. There will be a charge of $1.00 for each 1,000 gallons of water used from the City's system, and a credit of $1.00 given for each 1,000 gallons of product water returned to the system. Charges for utilities will be at the municipal rate enjoyed by the City. Charges for commodities and parts will be at cost to the City. City purchases are not subject to sales tax and are generally effected at discount.

(2) **Labor** at $12.00 per man-hour. This includes installation as well as operating work done specifically for a project.

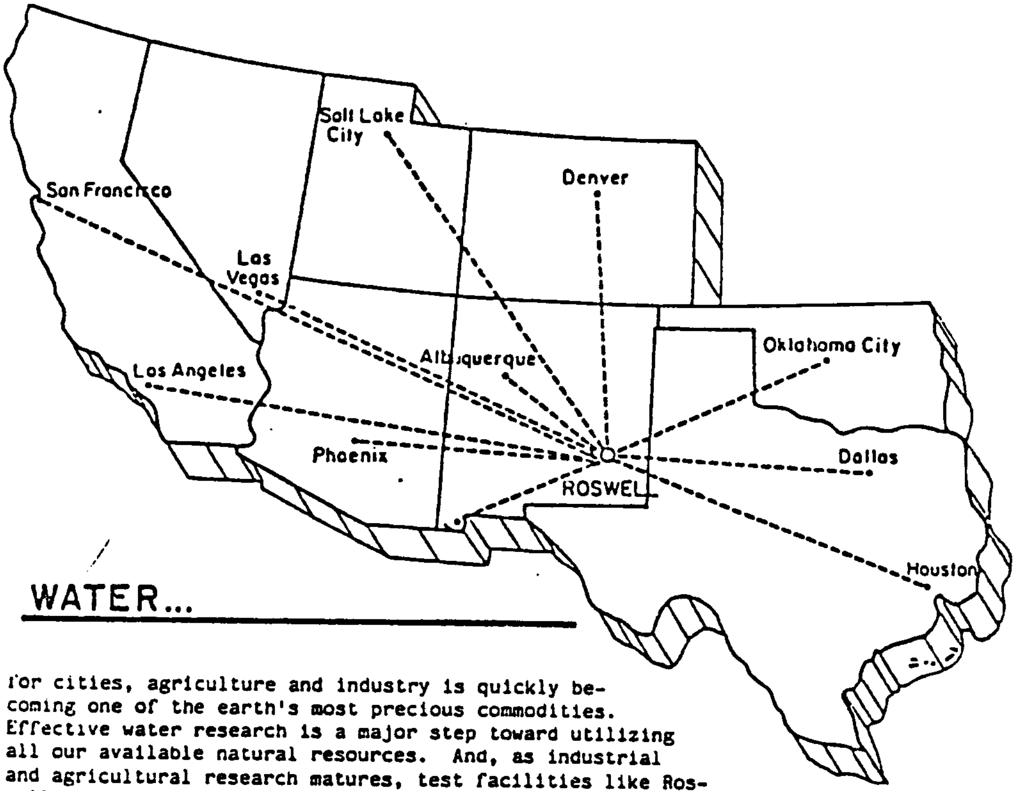
(3) **Laboratory Analysis** as per schedule of charges. For analysis not scheduled, the charge is $15.00 per hour labor. Mr. Isaacs, the City Chemist, has been employed at the RTF for 12 years.

(4) **Space Rental** at $1.00 per square foot for research facilities and $3.00 per square foot for office facilities.

(5) **Overhead and Management** at 6½% of the aggregate of the charges above.

Further questions should be directed by mail to Roswell Test Facility, City Utilities Department, P. O. Drawer 1838, Roswell, New Mexico 88201, or by telephone at (505) 623-0531.

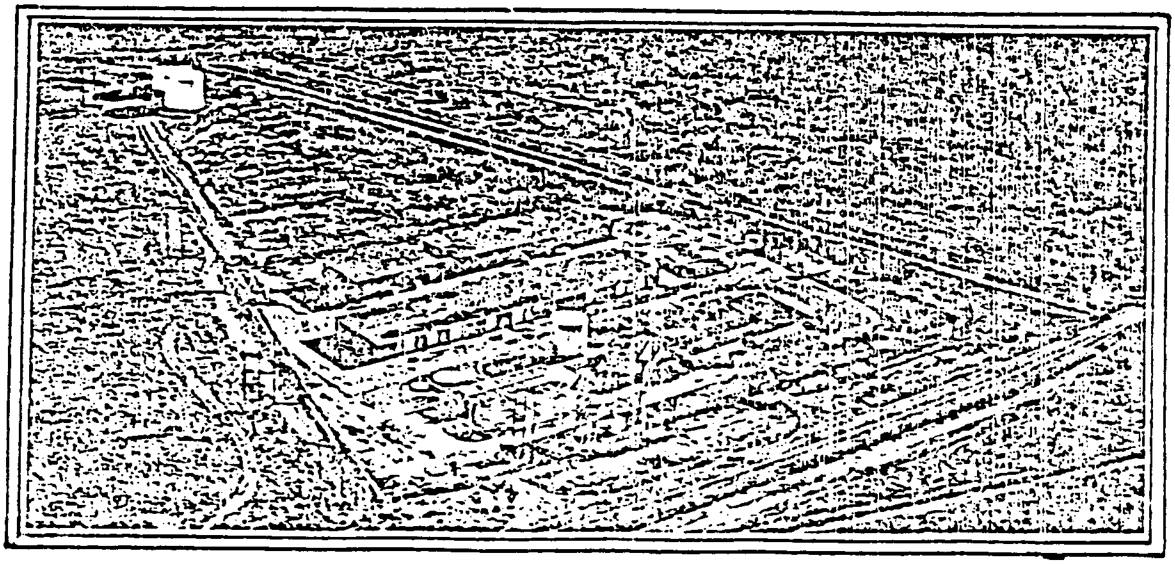
THE ROSWELL
NEW MEXICO
TEST FACILITY



WATER...

For cities, agriculture and industry is quickly becoming one of the earth's most precious commodities. Effective water research is a major step toward utilizing all our available natural resources. And, as industrial and agricultural research matures, test facilities like Roswell's will become increasingly valuable. It can meet almost any need for high-quality or brackish water and provide a controlled atmosphere for gathering and analyzing data.

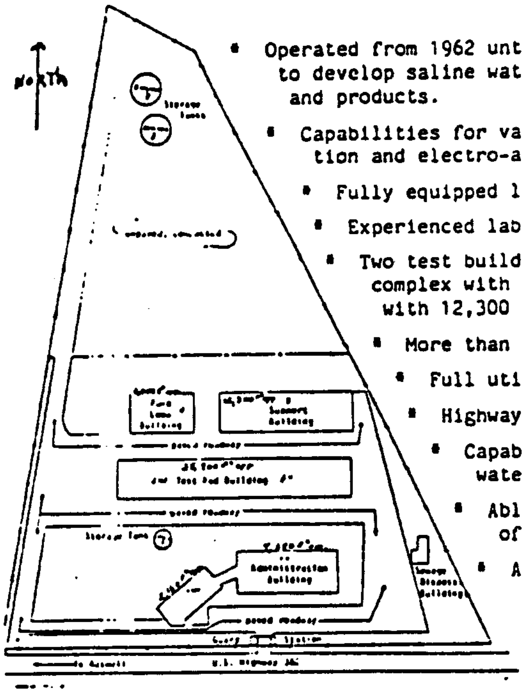
This laboratory is now available to public institutions and private industry for research!



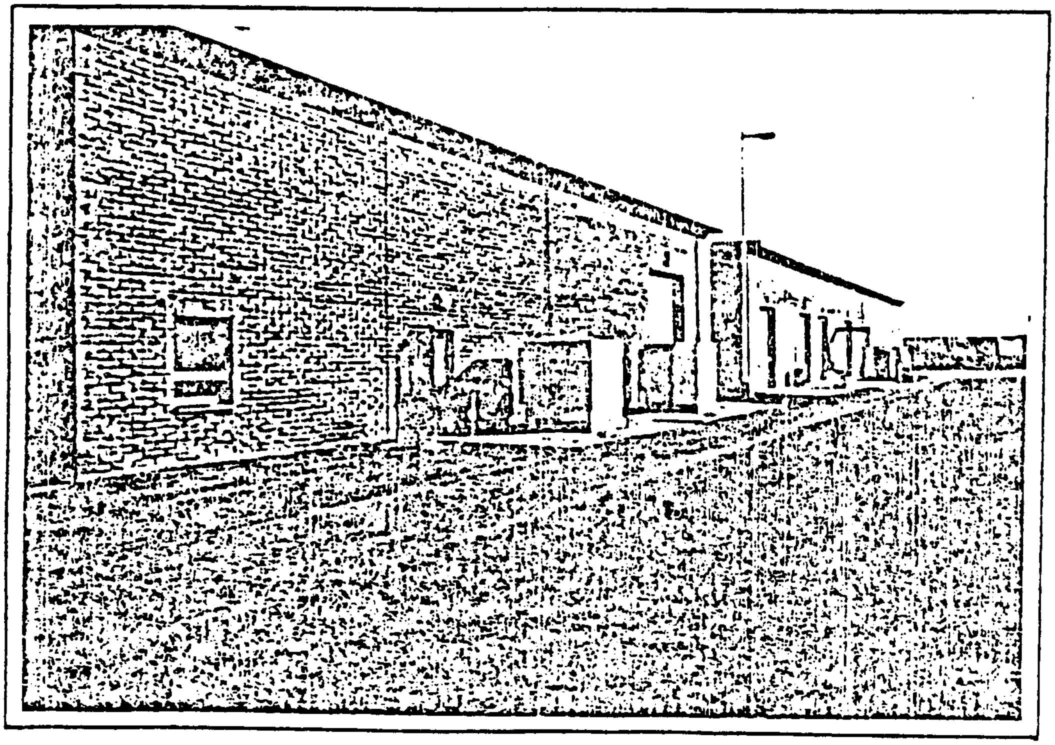
THE FACILITY...

The Roswell Test Facility is a unique research installation capable of replicating a wide range of brackish water conditions.

The Roswell Test Facility blends and mixes water qualities to meet the most exacting needs of research and industry.



- Operated from 1962 until 1982 by the U.S. Department of the Interior, to develop saline water conversion technology, and related processes and products.
- Capabilities for vapor-compression distillation, reverse osmosis desalination and electro-analysis testing.
- Fully equipped laboratory containing 1200 sq. ft.
- Experienced laboratory support staff available.
- Two test buildings with 25,900 sq. ft., an administrative office complex with 6,000 sq. ft., a support and maintenance building with 12,300 sq. ft., and a wastewater treatment facility.
- More than 12 acres of fenced area with additional land available.
- Full utilities at reduced public rates.
- Highway access to site.
- Capable of producing 300,000 gallons daily of high quality water.
- Able to process, blend and mix to achieve water qualities of 50 ppm to 30,000 ppm.
- Able to achieve pressures from 50 psi to 800 psi and higher.



COMPATIBLE USES...

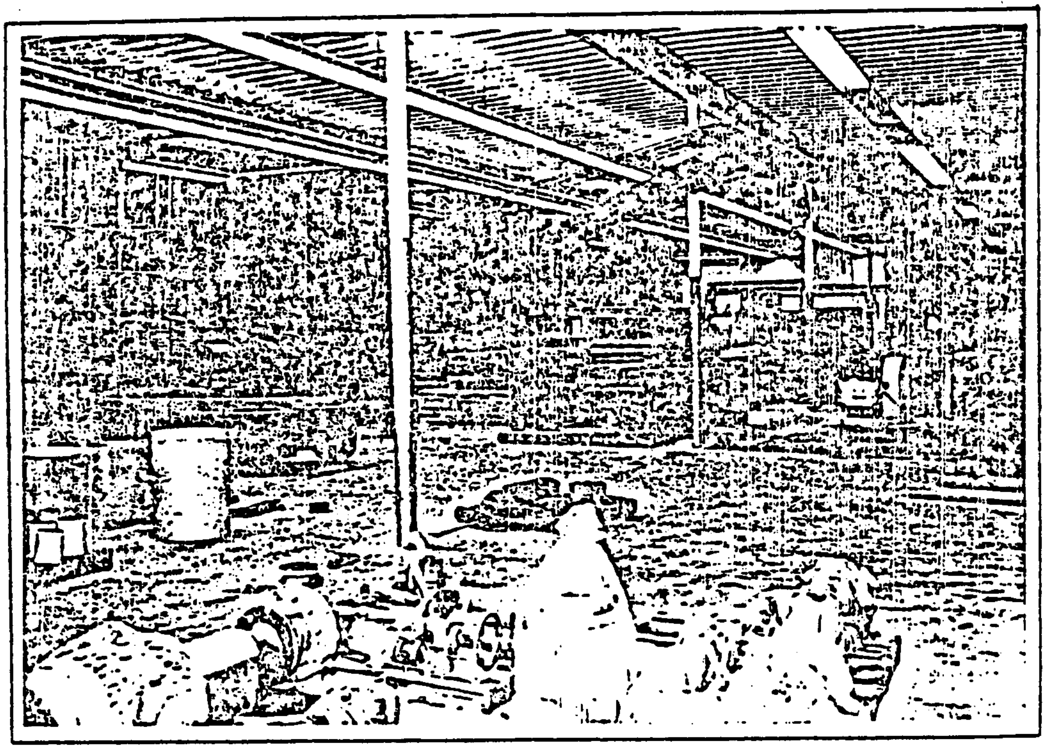
THE ROSWELL TEST FACILITY

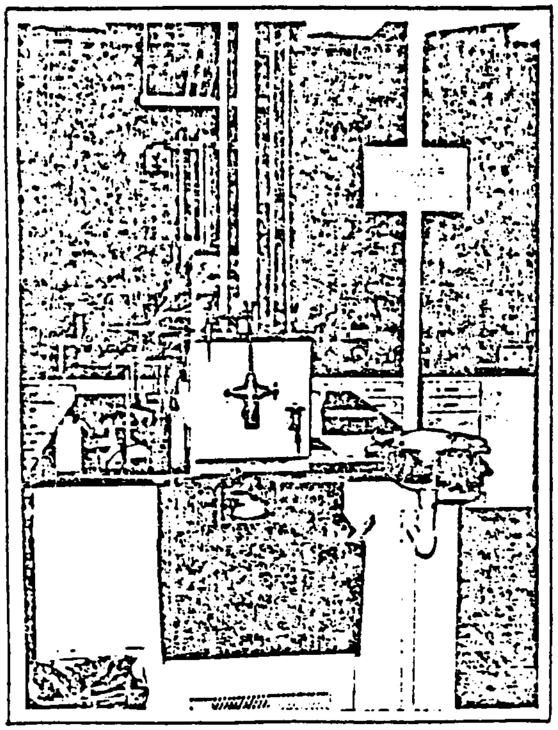
CAN ACCOMODATE YOUR NEEDS WITH

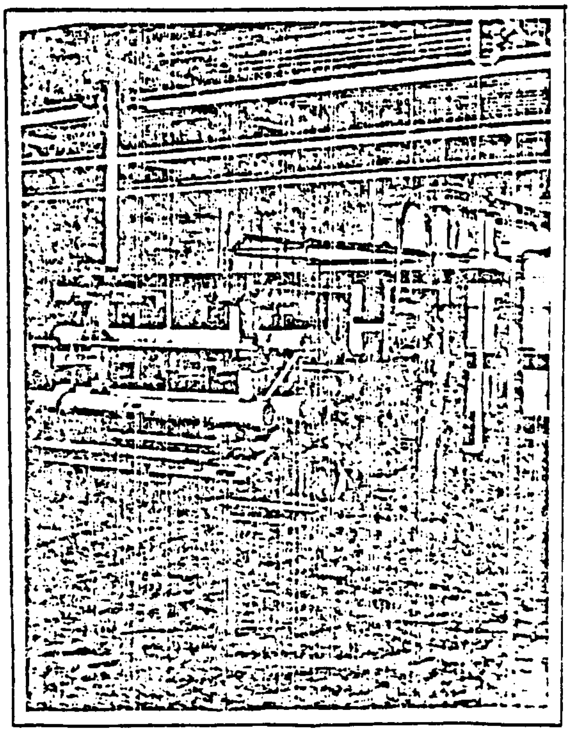
- FACILITIES
- LABORATORY
- WATER REPLICATION

CAN SERVE:

- ELECTRONICS
- PHOTO OPTICS & PHOTOGRAPHY
- AGRICULTURE, HYDROPONICS & AQUACULTURE
- OIL AND NATURAL GAS PRODUCTION
- CORPORATE & ACADEMIC RESEARCH
- WATER RELATED TESTING
- CHEMICAL TESTING & PRODUCTION





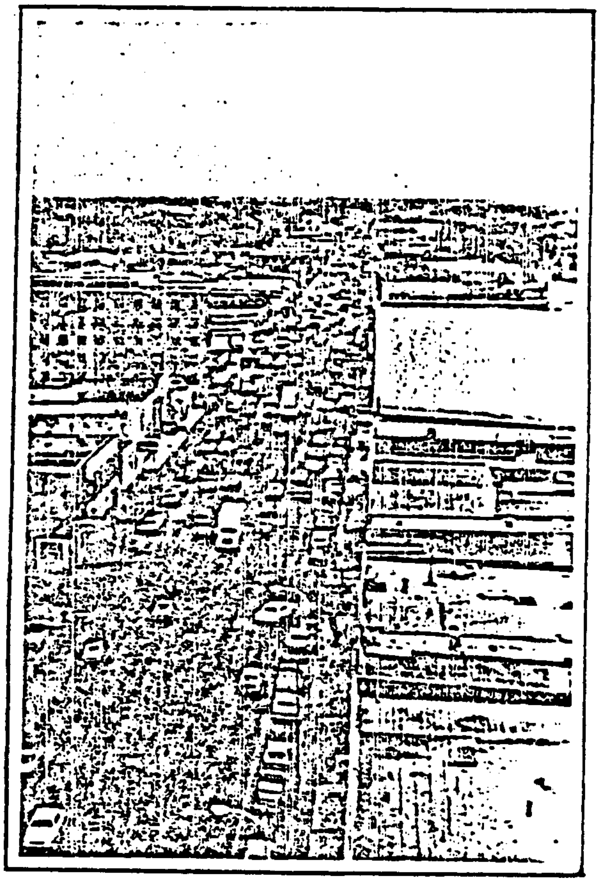


COMMUNITY PROFILE...

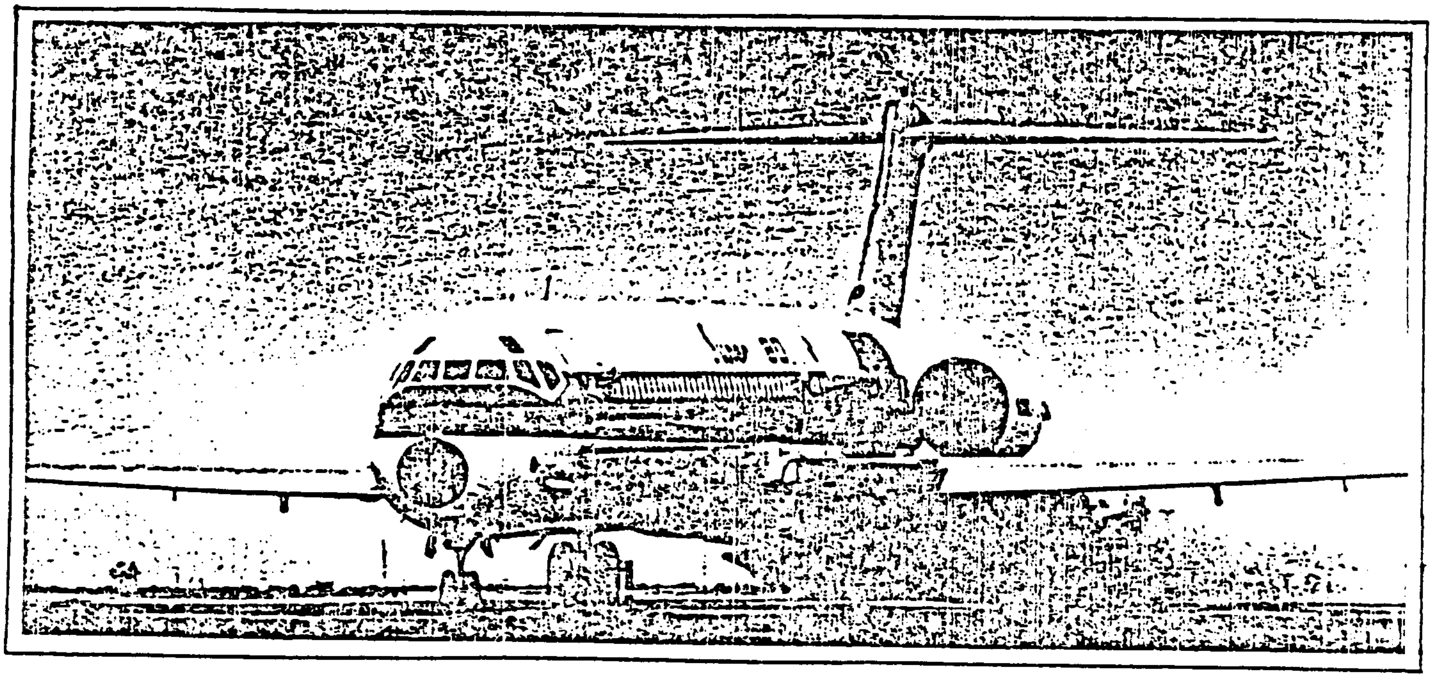
- Population: 48,100
- Work Force: 21,578
- Commercial Banks: 5
- Savings & Loan Associations: 4
- Rail Service: AT&SF, with spurs to the Roswell Industrial Air Center
- Highways: U.S. 70, 285, 280
- Airport Facilities: Municipal Airport with nine daily connecting flights to Regional/International Airports
- Motor Freight Carriers: 5
- Higher Education: Eastern New Mexico University/Roswell, New Mexico Military Institute
- Major Industries:

TMC	Bus Mfg.
Levi Strauss	Apparel Mfg.
Holsum Bakery	Bakery Products
Transwestern Pipeline	Natural Gas Transmission
K.B. Kennedy Engineering	Gas Refining

- Climate: Average Annual Temperature: 74.4°F
  Average Annual Precipitation: 12"
- Regional Shopping Center Serving 130,000 population



The Roswell community is a regional economic development center with THE PEOPLE necessary to serve your needs and THE FACILITY designed to be compatible with the requirements of your industry.



FOR FURTHER INFORMATION CONTACT:

JIM WHITFORD, CITY MANAGER
CITY HALL
P.O. BOX 1838

APPENDIX H

Design of Experimental Anaerobic Digester for Microalgae

IGT
Headquarters

February 26, 1985

Mr. Frederick M. Mencher
Aquaculture Associates, Inc.
1110 Richards Street
Room 206
Honolulu, HA 96813

Dear Fred:

This is in response to your letter of February 18, 1985 regarding a microalgae digestion system to produce approximately 15 gallons of effluent per day. Attached is a process scheme showing all the necessary tanks, pipings, and design information for all the tanks. As you can see from the flow diagram, this digester can be operated in either upflow or downflow mode and is capable of providing hydraulic mixing. A mechanical mixer can be mounted on the top of the digester if desired. Similarly, the feed tank contents can also be mixed hydraulically and a mechanical mixer may not be necessary. However, this depends on the physical properties of the feed slurry.

The cost of this system can be controlled by operating most of the equipment manually, having only a few automatic controls, and also by using inexpensive materials of construction. The cost of training someone at IGT depends on the total number of days an operator spends at IGT. We feel that at least one IGT employee (preferably a full professional) will have to be with the operator at all times. Considering that, plus IGT's overhead, G&A, and fee, it would cost $2613.60 per week (this rate is effective through August 1985). If an IGT employee goes to the site, the total cost per week will be $2613.60 plus air fare and living expenses for one week.

I hope this information answers your questions. If I can be of further assistance, please call me.

Sincerely,

Vipul J. Srivastava

V. J. Srivastava
Supervisor,
Biotechnology Research
(312) 567-5282

VJS:pf
Encls.
cc: R. B. Spencer
D. P Chynoweth
Z. Toliusis

Institute of Gas Technology

Headquarters
3424 South State Street
Chicago Illinois 60616
312/567-3650
TELEX 25-6189

Energy Development Center
4201 West 36th Street
Chicago Illinois 60632
312/890-7000

Washington Office
1825 K Street, N.W.
Washington, D.C. 20006
202/785-3511

Affiliated with
Illinois Institute of Technology

DESIGN INFORMATION FOR ANAEROBIC DIGESTION SYSTEM FOR MICROALGAE

Basis: Production of approximately 15 gallons of digester effluent per day

Digester Loading: 0.20 lb VS/ft^3-day[a]

Active Digester Volume	30 ft^3
Suggested Digester Tank Volume	38 ft^3
Type of Digester Tank	Jacketed[b]
Digester Height/Diameter Ratio[c]	2 to 3
Feed Tank Volume[d]	2.5 ft^3
Feed Tank Height/Diameter Ratio[c]	2
Effluent Settling Tank Volume[e]	2.5 ft^3
Settling Tank Height/Diameter Ratio[c]	3

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[a] Not an optimum loading.

[b] Digester temperature control via hot/cold water recirculation is preferred.

[c] Depends upon the rheology of the slurry.

[d] Assumes daily (7 days/week) feed preparation is possible.

[e] Assumes daily (7 days/week) effluent withdrawal is possible.