Large Scale Open Algae Ponds

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The National Institute of Oceanography

Nature Beta Technologies Ltd.

Nikken Sohonsha Co, Japan

Seambiotic Ltd.

ISRAEL

Commercial Open Ponds

Taiwan

from round ponds (1960)
to
oblong raceways (1970)
mixotrophic cultivation

Biology & Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

- **Location**
- **Area layout**
- **Pond design**
- **Oblong raceways [length (10-300m), width (1-20m)]**
- **Optimal size area (300-4,000m^2)**
- **Distal end, hydraulic radius**
- **Ground infrastructure (area preparation)**
- **Pond lining (none, clay, concert, asphalt, fiberglass, plastic sheeting, others)**
- **Liquid flow (paddle wheels, pumps, airlift, moving board, others)**
- **Paddle wheel**
- **Outside walls and channel dividers**
- **Flow velocity (laminar liquid flow velocity, 5-40 cm/sec)**
- **Site control, pH control**
- **Carbonation**
- **Mixing & Turbulence**
- **Depth (5-100cm, depth control)**
- **Head loss, hydraulics, Manning's "n" values**
- **Pond accessories (drainage, cleaning, pumps, pipes)**

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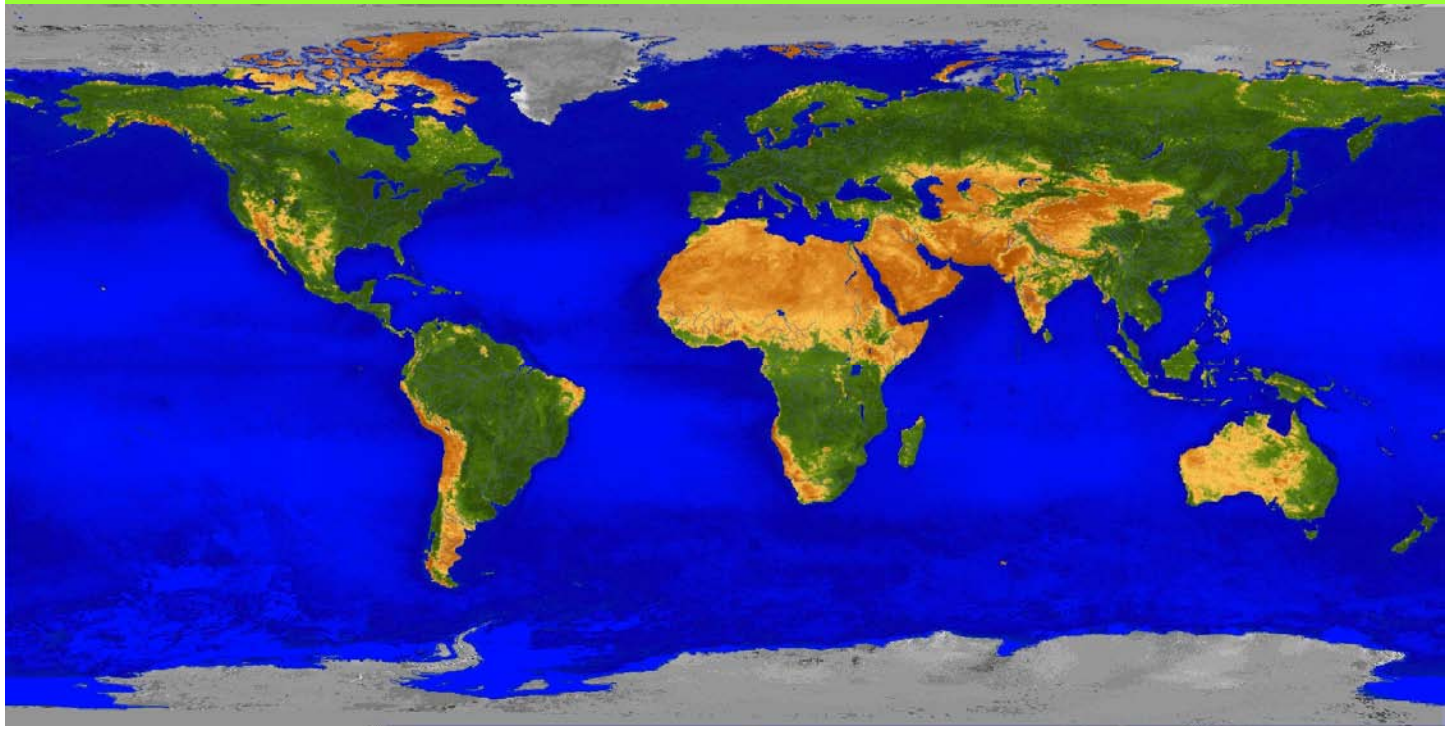
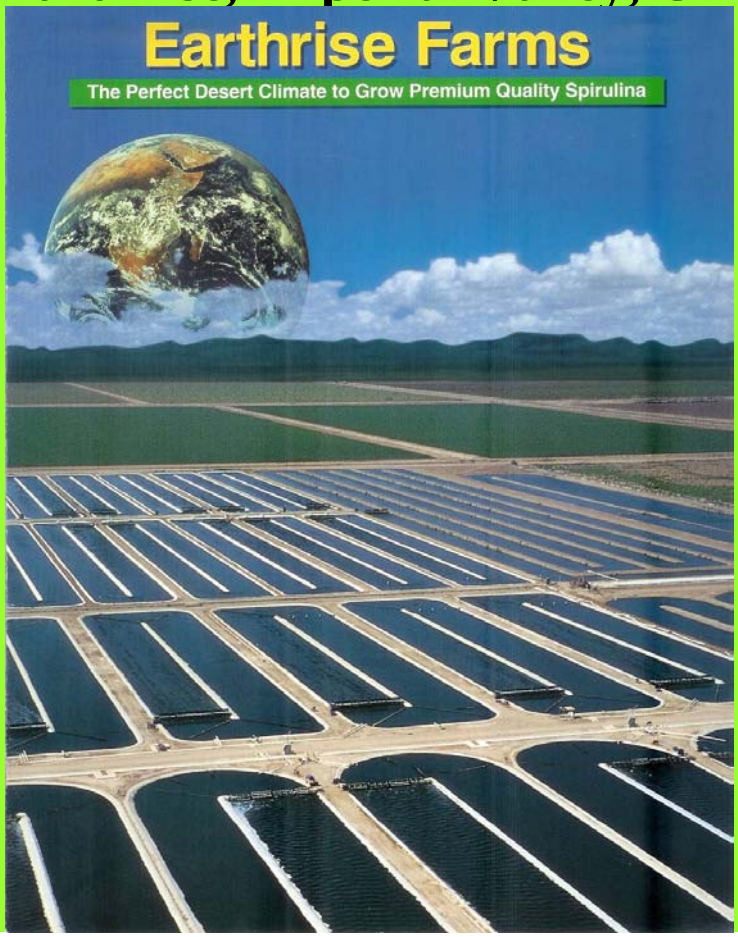
Location?

“Climatic regions most suitable for microalgae : annual average temperatures of > 15 °C” (Benemann, 2007)



Location?

Earthrise, Imperial Valley, CA



Location?
Microbio Resources, Imperial Valley, Calipatria, CA

Location?

Nature Beta Technologies Ltd., Eilat, Israel

Location?
Cyanotech Corp. Hawaii, USA

Location?
Far East *Chlorella* and *Spirulina*

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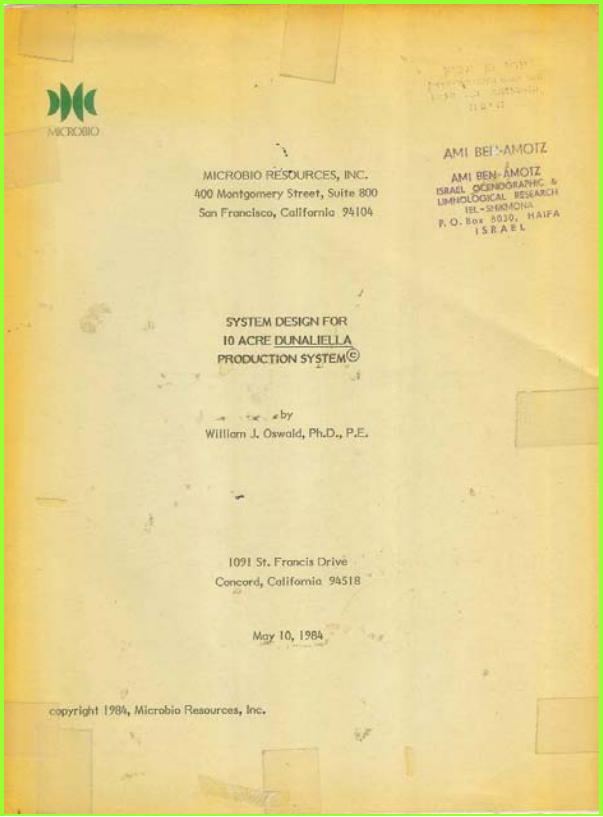
Design

U or Ellipsoid Pond?

pump, bubbling air or airlift?

Oswald, Shelef & Melamed, USA & Israel, 1977

Oswald (1983/4)
System Design for 10 Acres
Dunaliella Production System



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SYSTEM DESIGN FOR
10 ACRE DUNALIELLA
PRODUCTION SYSTEM©

by
William J. Oswald, Ph.D., P.E.

1091 St. Francis Drive
Concord, California 94518

May 10, 1984

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Raceway Pond
(Oswald 1984)

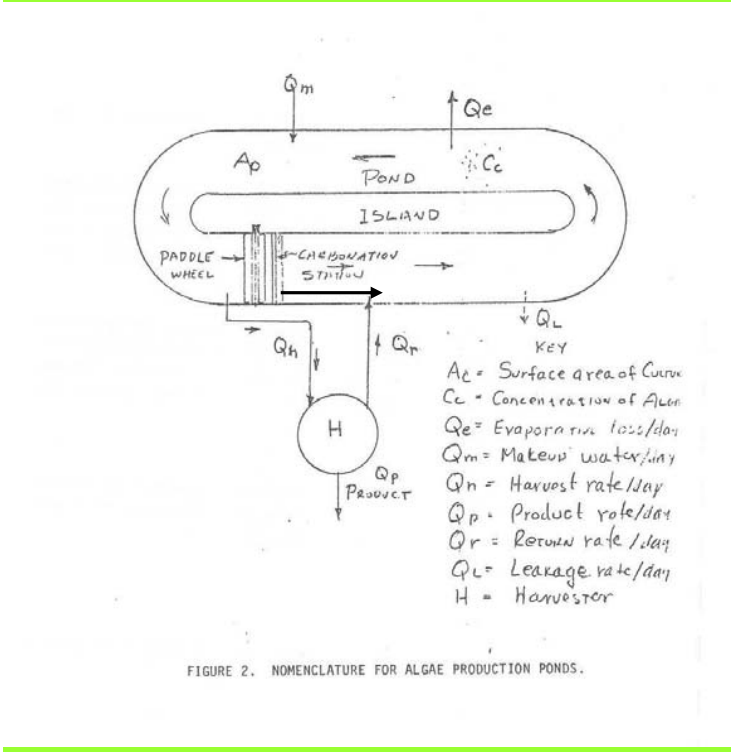
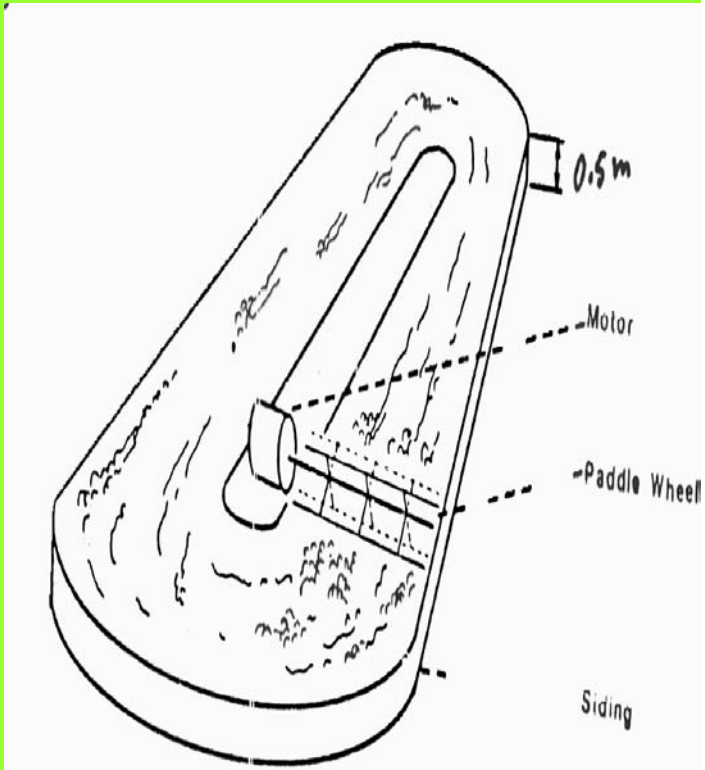
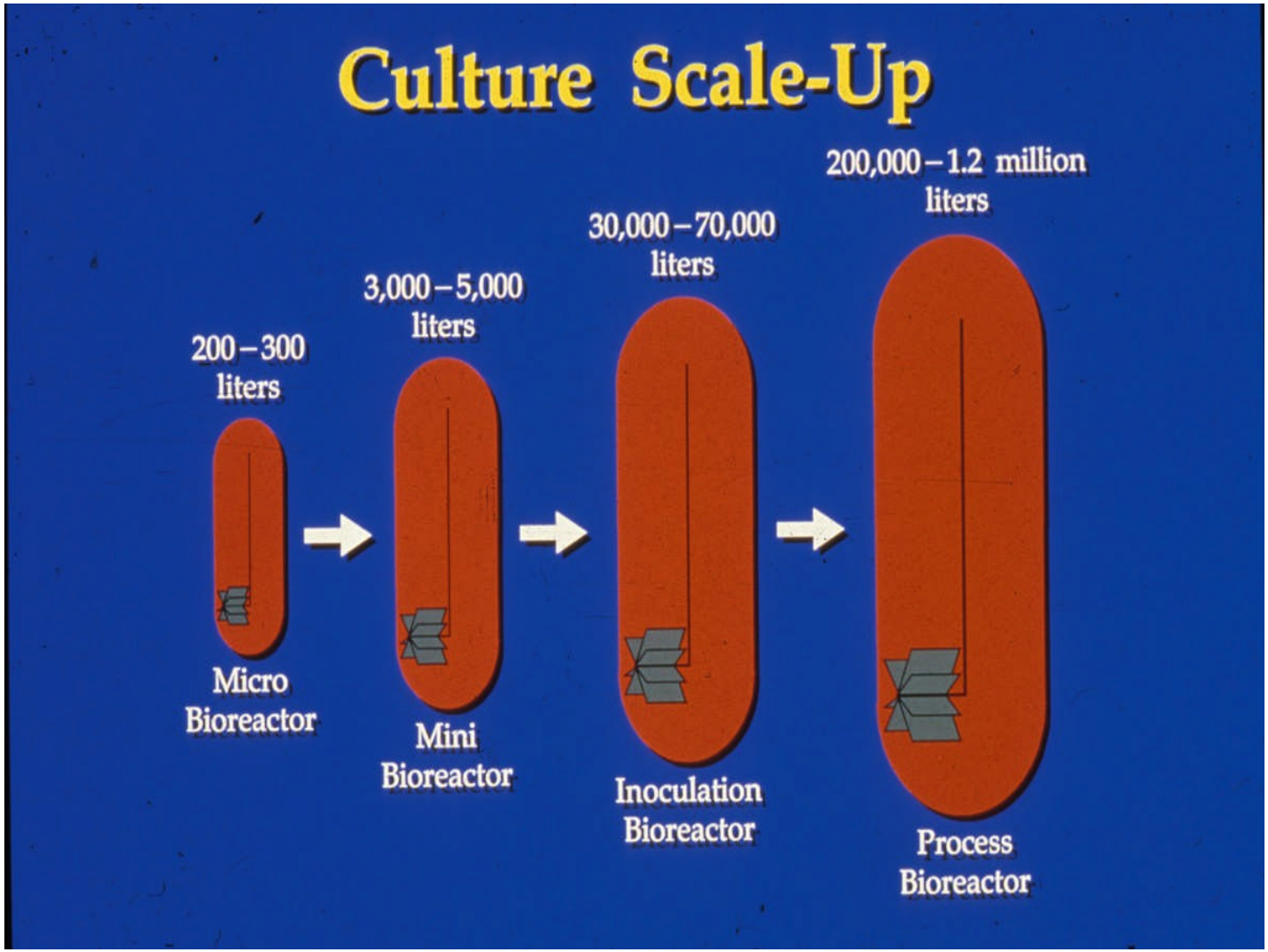


FIGURE 2. NOMENCLATURE FOR ALGAE PRODUCTION PONDS.




Culture Scale-Up
200 – 300 liters
Micro Bioreactor
3,000 – 5,000 liters
Mini Bioreactor
30,000 – 70,000 liters
Inoculation Bioreactor
200,000 – 1.2 million liters
Process Bioreactor

Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

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Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

Area Layout & Pond Design, set of <u>1 acre ponds</u> (Oswald 1984)

Major items:

- Up & Down streams
- Overflow sumps
- Fresh water makeup
- Paddle wheels
- Carbonation
- CO_2 feed lines
- Solids chamber
- Liquid lines
- Length, width, depth, slope,
- Screens

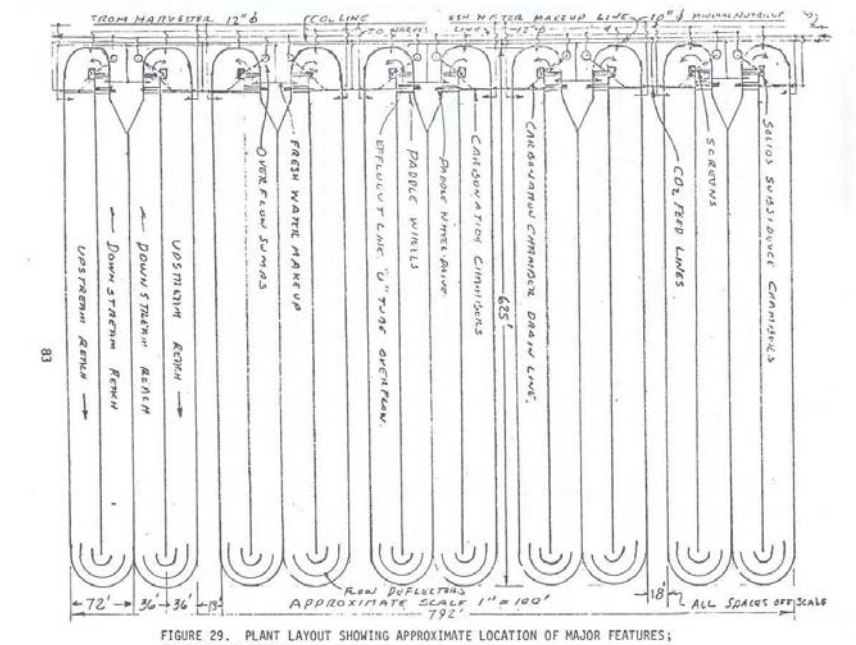


FIGURE 29. PLANT LAYOUT SHOWING APPROXIMATE LOCATION OF MAJOR FEATURES; ALL UNITS IDENTICAL.

Length, Width & Depth

Length and Width:

To develop the lengths of the units, recall that 1 acre = 43,560 ft.^{2}, therefore 10 acres = 435,600 ft^2 and the length of one side of a square 10 acre plot is $\sqrt{435,600}$ = 660 ft : to allow for end construction use, one acre plot 623 ft long will be 43560/623 = 70 feet wide. And since there will be 2 parallel channels in each pond, each channel will be about 35 feet wide. Total mean water path length through this circuit will be (623 + 35) x 2 = 1,316 feet. These lengths and widths are only approximate.

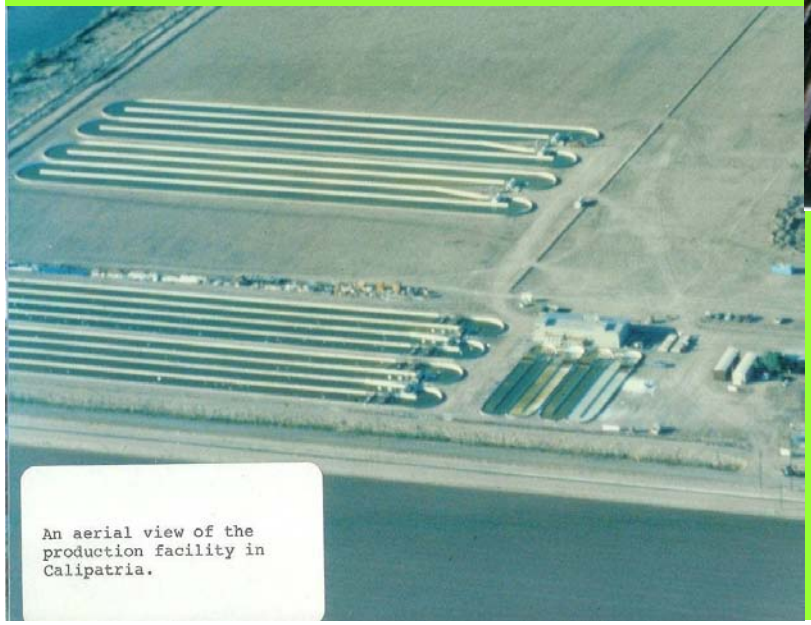
The length of channel, its roughness or "n" value, and the flow velocity to be used determine hydraulically permissible depths. The general relationships derived from Mannings equation for open channel flow are shown in Equation 13:

$$h_L/L = V^2/(1.486/n)^2 R^{4/3} \qquad (13)$$

in which h_L is the head loss in feet, L is the channel length in feet, V is the flow velocity in the channel in feet per second, n is the roughness coefficient for the channel (dimensionless), R is the hydraulic radius. Each of these factors is discussed below.

Length & Width

10 x 2 x 170 m = 3,400m^2 (USA)

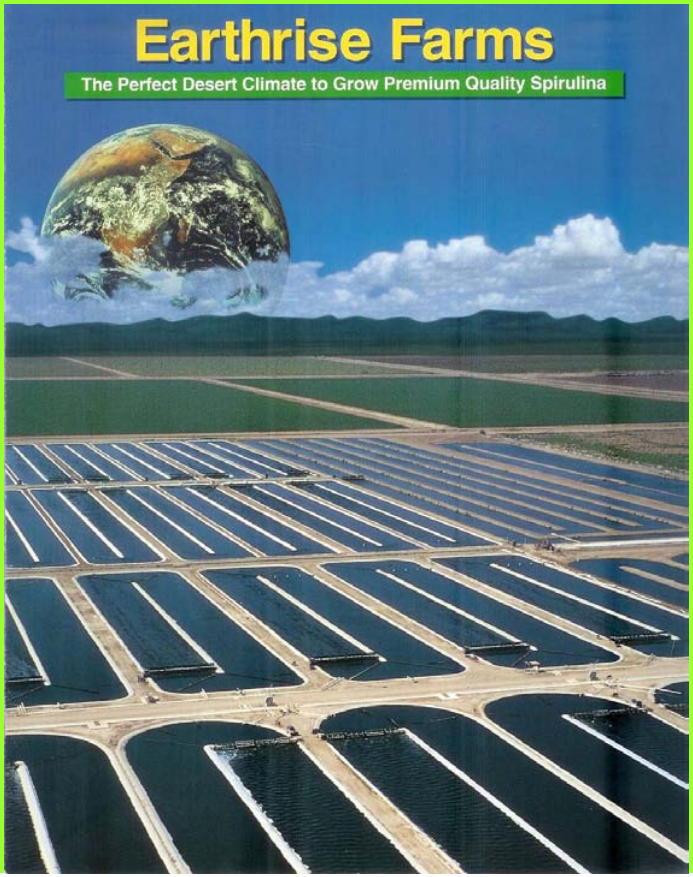


Length & Width

10 x 2 x 150 m = 3,000m^2 (Israel)

Length & Width

10 x 2 x 150 m = 3,000m^2 ?(USA)

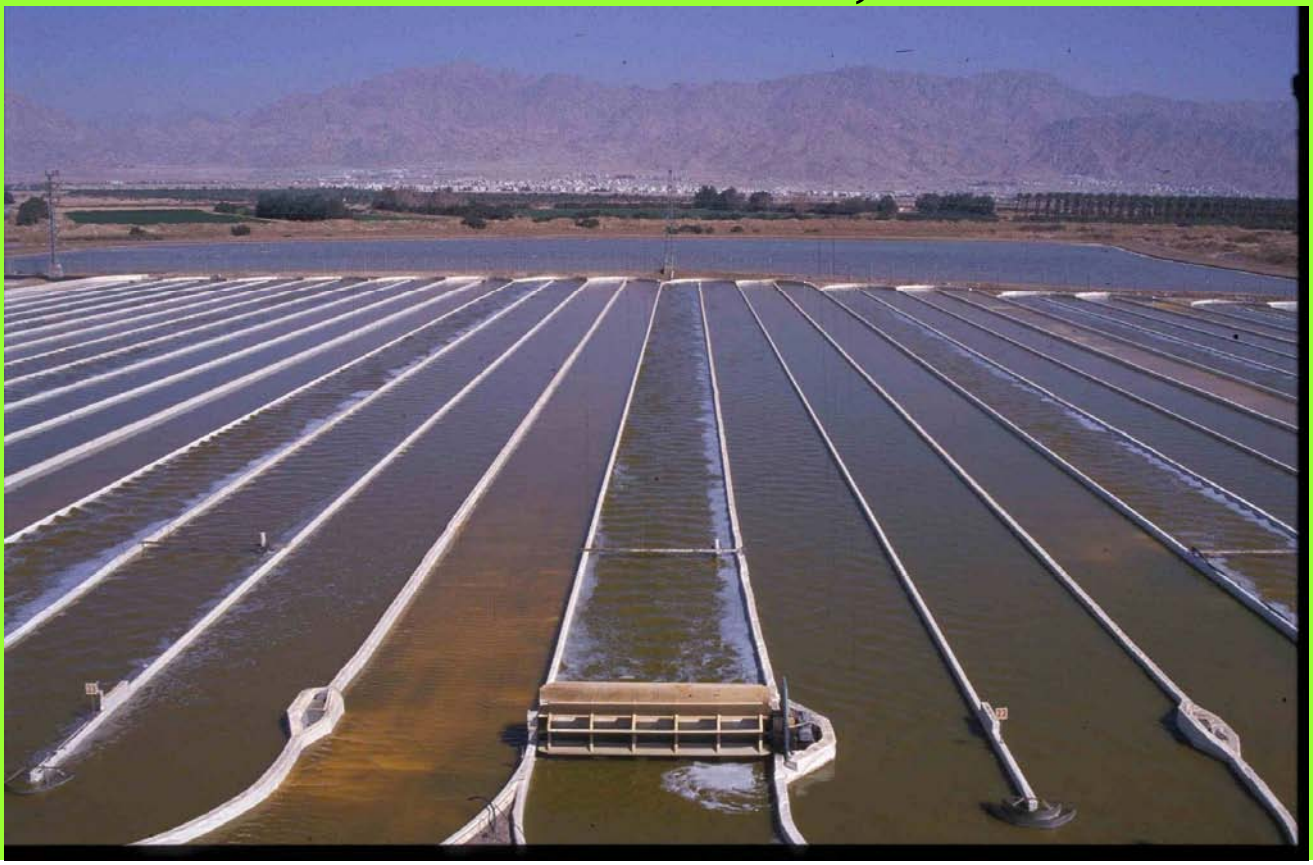


Scale Up, Length & Width

10 x 2 x 150 m = 3,000m^2 (Israel, USA)

Length & Width

5 x 4 x 150 m = 3,000m^2



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- **Carbonation**
- **Site control, pH control**
- **Pond accessories (drainage, cleaning, pumps, pipes)**

Distal End, Hydraulic Radius

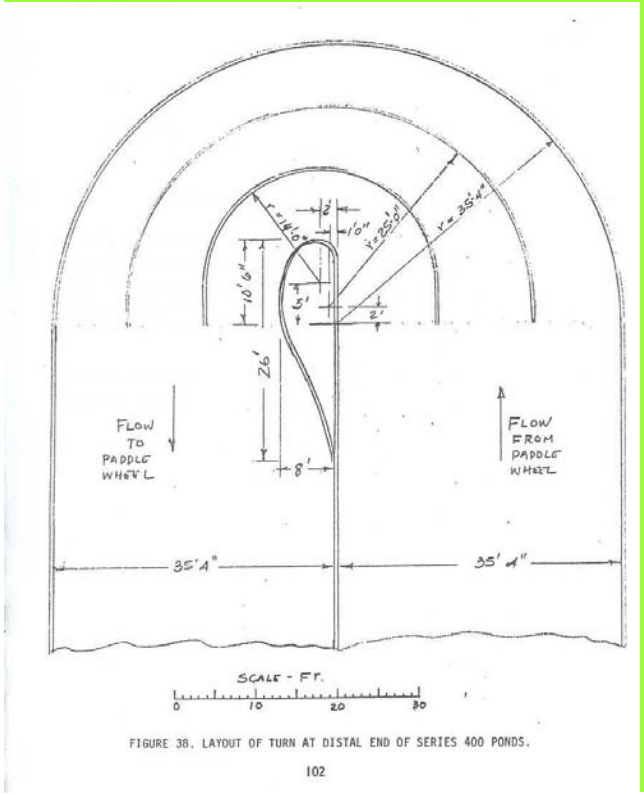

FIGURE 38. LAYOUT OF TURN AT DISTAL END OF SERIES 400 PONDS.

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No liner
Clay

Asphalt

PVC & PE

PVC, under liner geo-textile

300 m^2 Pond

PVC

3,000m^2

PVC Liner 20 Years Old
Durable (20 years), UV resistant, Low “n”

Biology &Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

Pond lining

None, leak

Clay, leak, anaerobic areas

Concert, break

Asphalt, disintegrate

Fiberglass, expensive

Rubber, ??

High density polyethylene (HDPE), break, high temperature expansion coefficient

Polyethylene, ok, low "n" but welding problem

Polypropylene, ok, low "n"

PVC (technical grade, food grade), ok, low "n"

PVC, Geo-textile underline, may be needed

PVC, UV resistance, ease of maintenance, simlpe welding, durable

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Biology & Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

The Paddle wheel

- **“Inefficient pump” or independent impeller**
- **Location**
- **Design**
- **Construction**
- **Shaft & blades material (stainless steel, fiberglass, marine plywood, others)**
- **Number of blades**
- **Diameter**
- **Bottom to paddle distance**
- **Paddle in liquid (perimeter & angle, immersion in culture)**
- **Salt incrustation (water washing)**
- **Motor, gear, rpm (5-30rpm)**
- **Maintenance (weight, lifting, lift distance)**
- **Units/pond**
- **Units/area**

The One Unit Paddle Wheel

Oswald (1983)

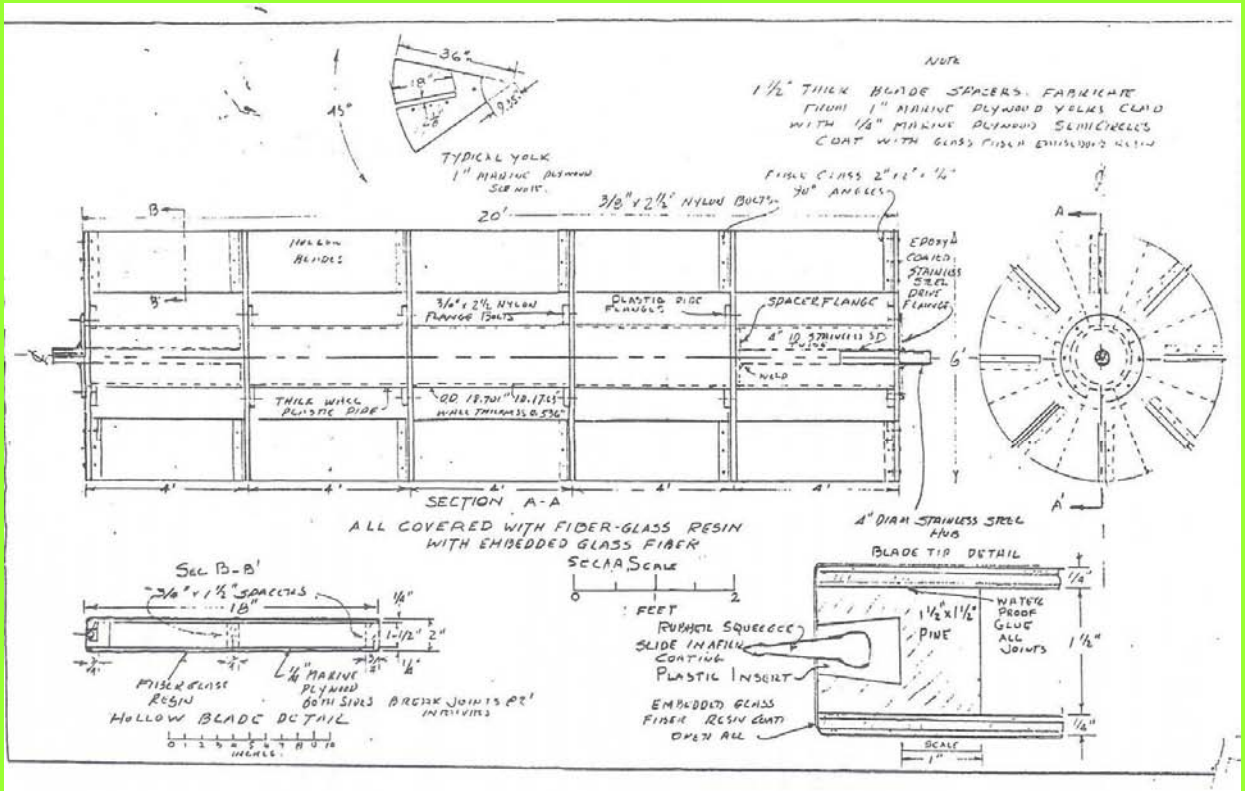

FIGURE 37. PADDLE WHEELS.

The Paddle Wheel Location and Design

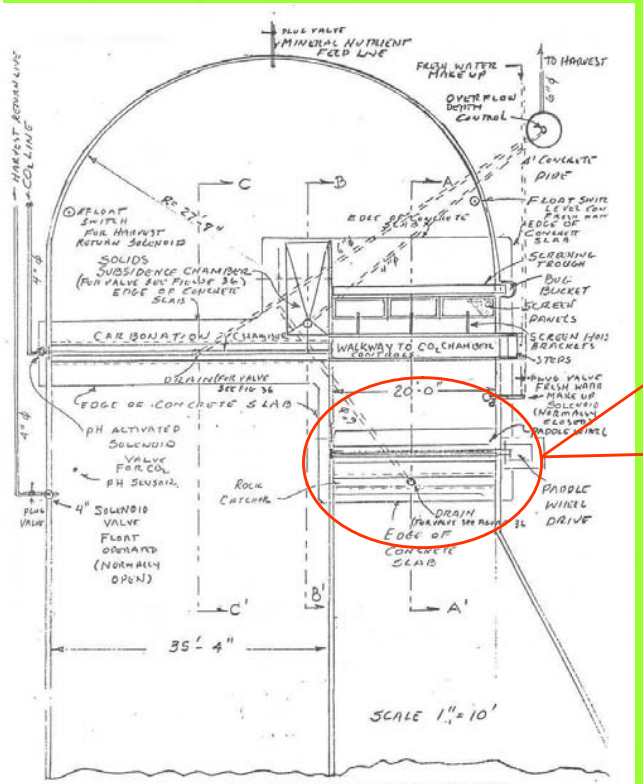

FIGURE 34. LOCATION OF MAJOR FEATURES IN 1 ACRE PONDS.

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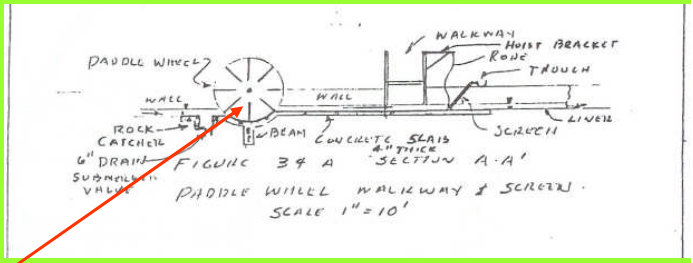
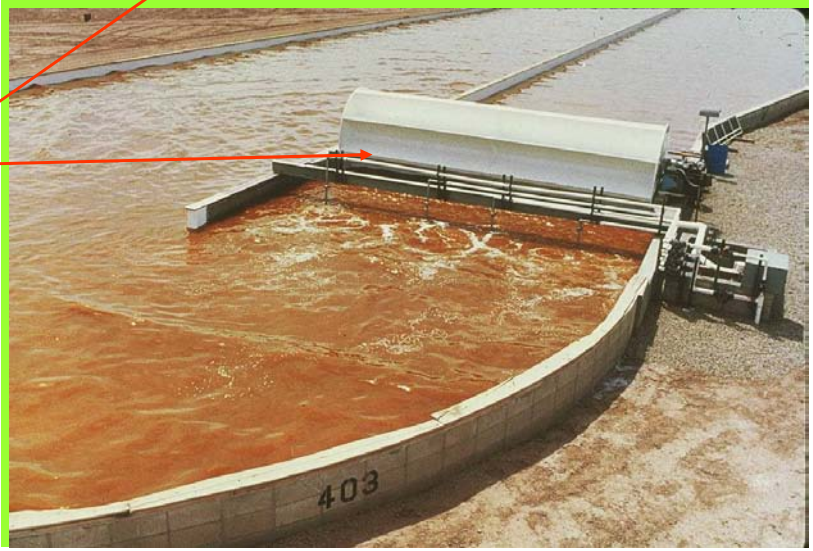


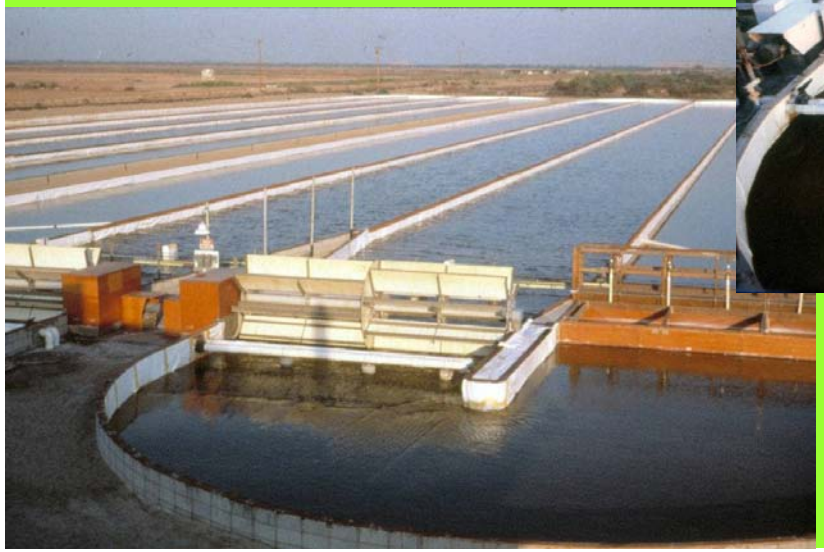


The Paddle Wheel

one unit fiberglass paddle (Oswald)
or the divided blades

motors & gears

The Paddle Wheel Material
Blades made of plastic, metal or marine plywood (Dodd)



The Paddle Wheel Dimensions

Length: 10 or 5 meters?

One of 5 or 10m, or two of 5m?

Diameter: 30 to 120cm?

Blades shape & size?

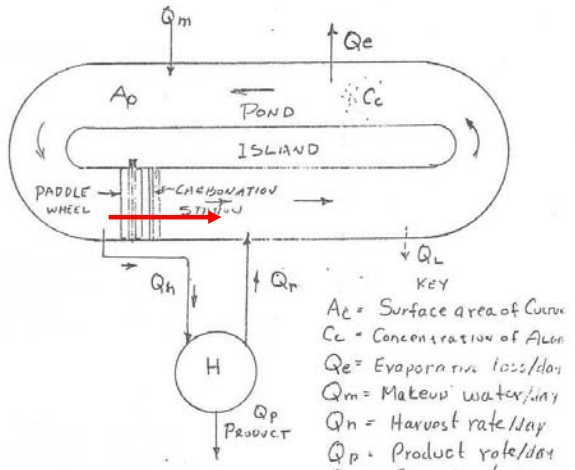
Immersion & angel?

The *Spirulina* Paddle Wheel
short diameter (30 cm), high rpm

Spirulina paddle
long, short diameter, high rpm

The Paddle Wheel
location, design, direction?
two or one in pond?

Paddle Wheel
flow direction?



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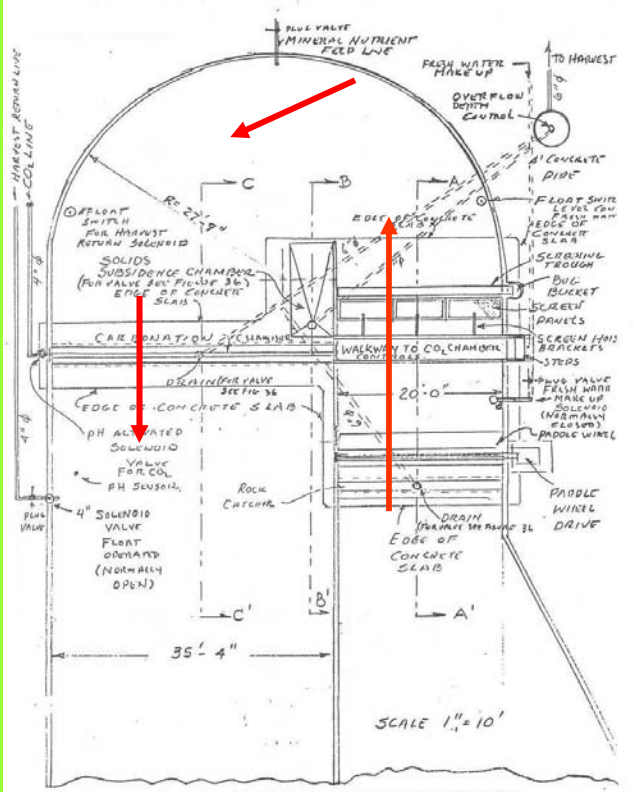

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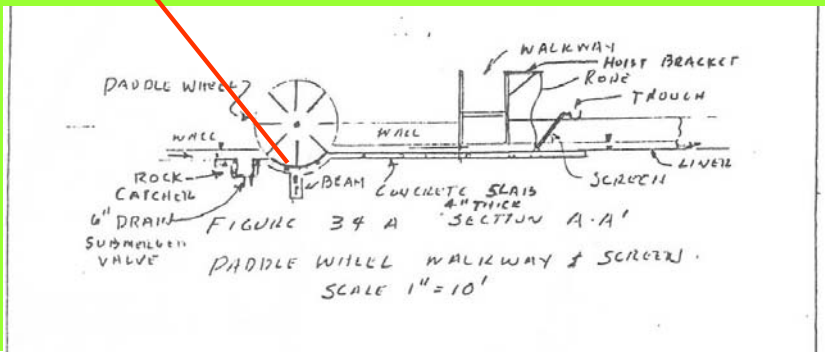
The “Island” design and area?

Pond Optimization
paddle wheel/pond area?
Oswald: one paddle/3,400m^2

Immersion, Angel and Ground

how many blades in culture at time (2/8;3/8;2/6)? distance to ground?



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Outside walls and channel dividers concrete?

Outside walls and channel dividers bricks?

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Laminar Flow Velocity
Oswald: ~30cm/sec

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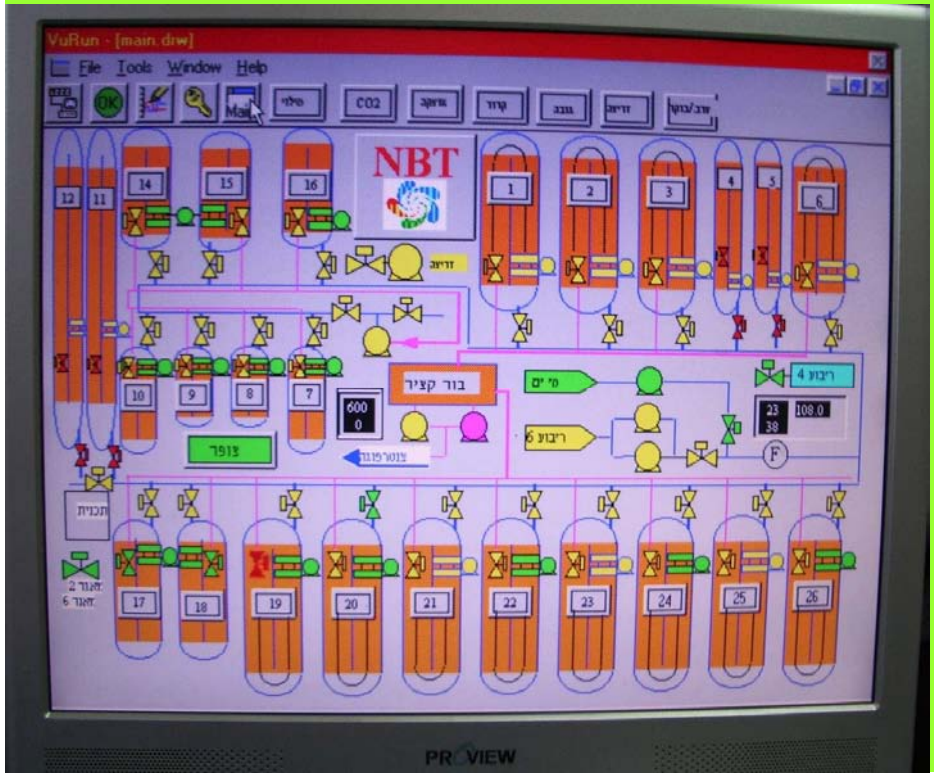
PC Site Control

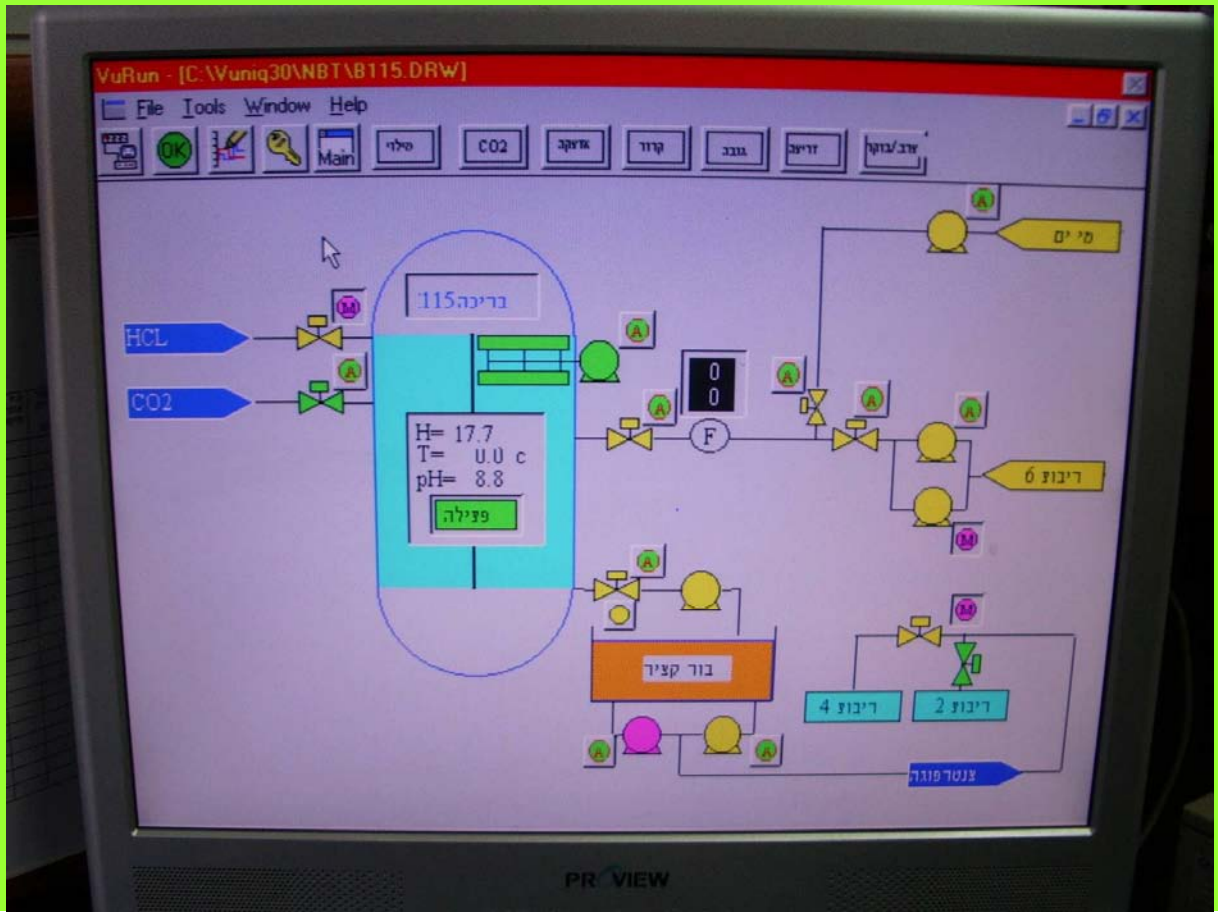
Technology control: paddles, pumps, pipes, gases, sensors, liquids

Biology information & control: pH, depth, CO_2 flow, temperatures, liquid transfer



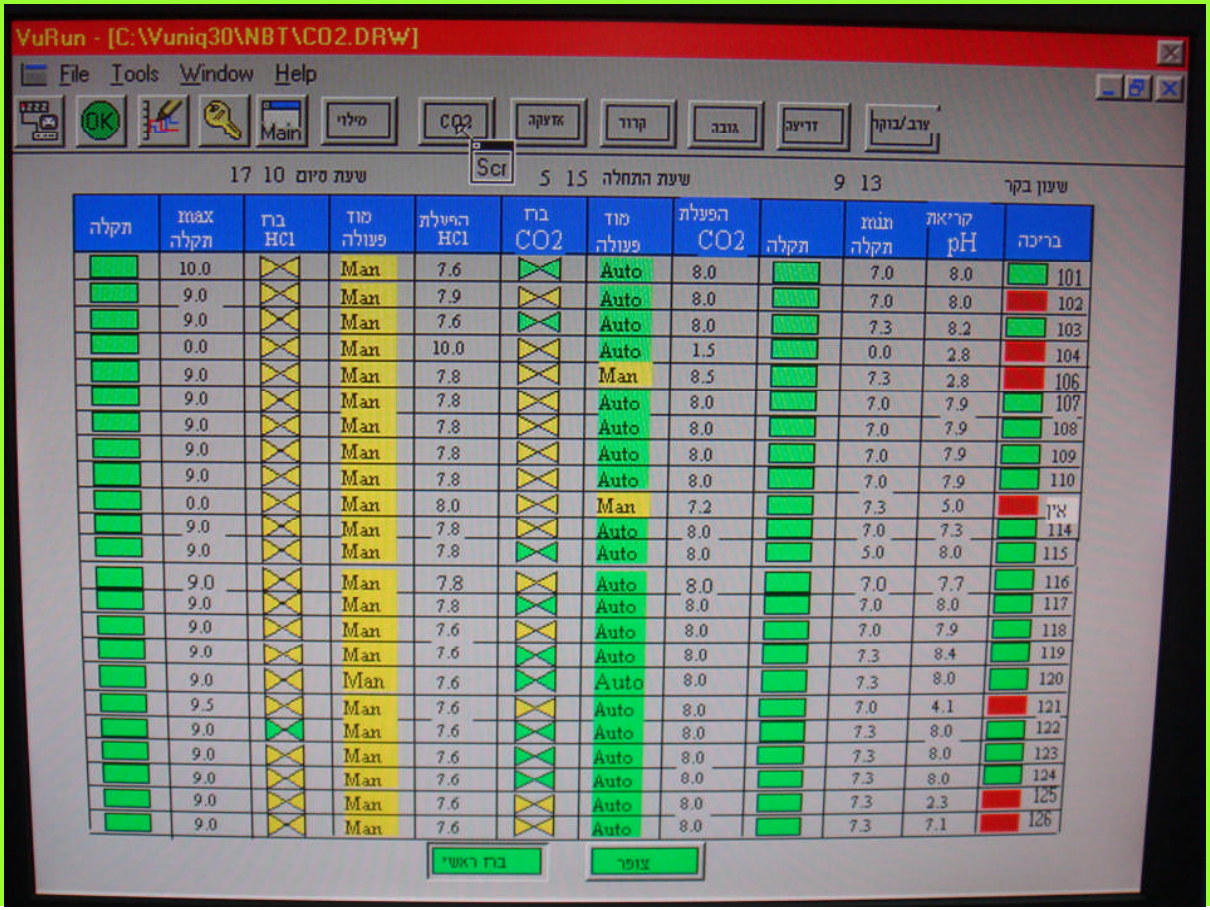
Site Control & Operation
liquids transfer control at 60m^3/hr

Dedicated Pond Control



CO_2 pH Control
depth control & sensors (wired, wireless)

pH Control, 10 Hectares



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- **Carbonation**
- **Depth (5-100cm, depth control)**
- **Head loss, hydraulics, Manning's "n" values**
- **Turbulence**
- **Pond accessories (drainage, cleaning, pumps, pipes)**

Carbonation
counter current carbonation chamber
(Oswald 1983)
(Theoretical use: ~ 2g CO2/gr AFDW algae)

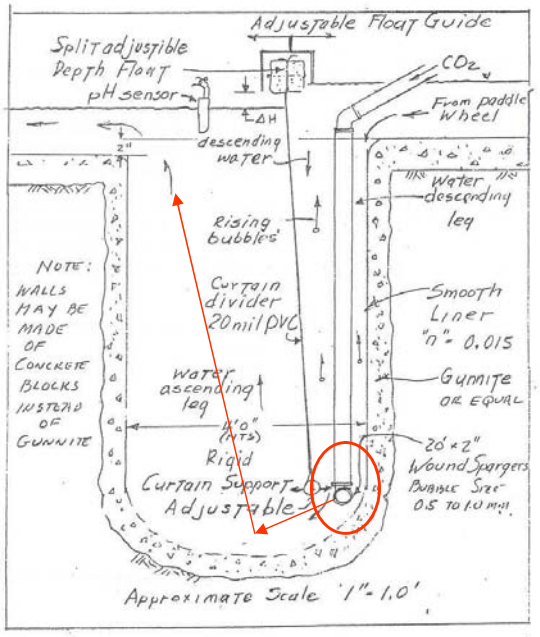


FIGURE 22. CROSS-POND COUNTER CURRENT ABSORPTION COLUMN FOR CO_2 TRANSFER WITH ADJUSTABLE CARBONATION CHAMBER VOLUME.

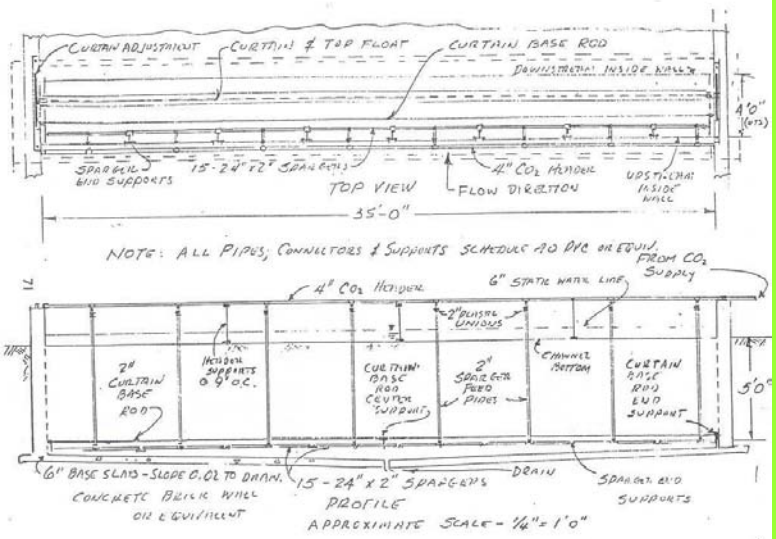


FIGURE 24. TOP VIEW AND PROFILE OF CARBONATION CHAMBER SHOWING CARBONATION SPARGER ARRANGEMENT AND DRAIN.

Carbonation

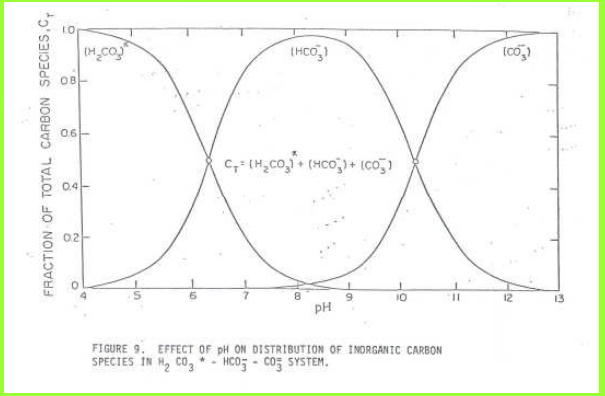
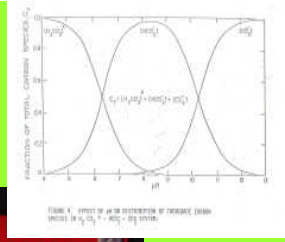
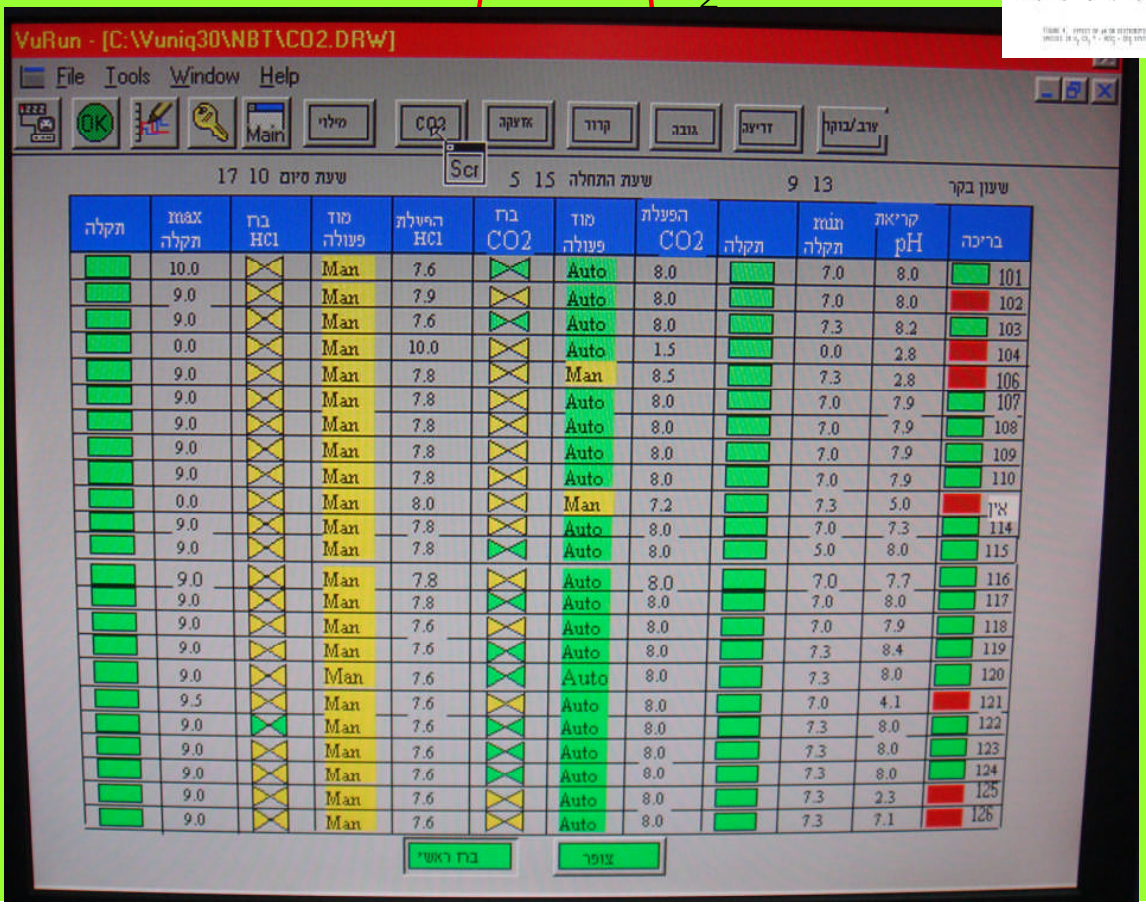


FIGURE 9. EFFECT OF pH ON DISTRIBUTION OF INORGANIC CARBON SPECIES IN $H_2CO_3^*$ - HCO_3^- - $CO_3^=$ SYSTEM.

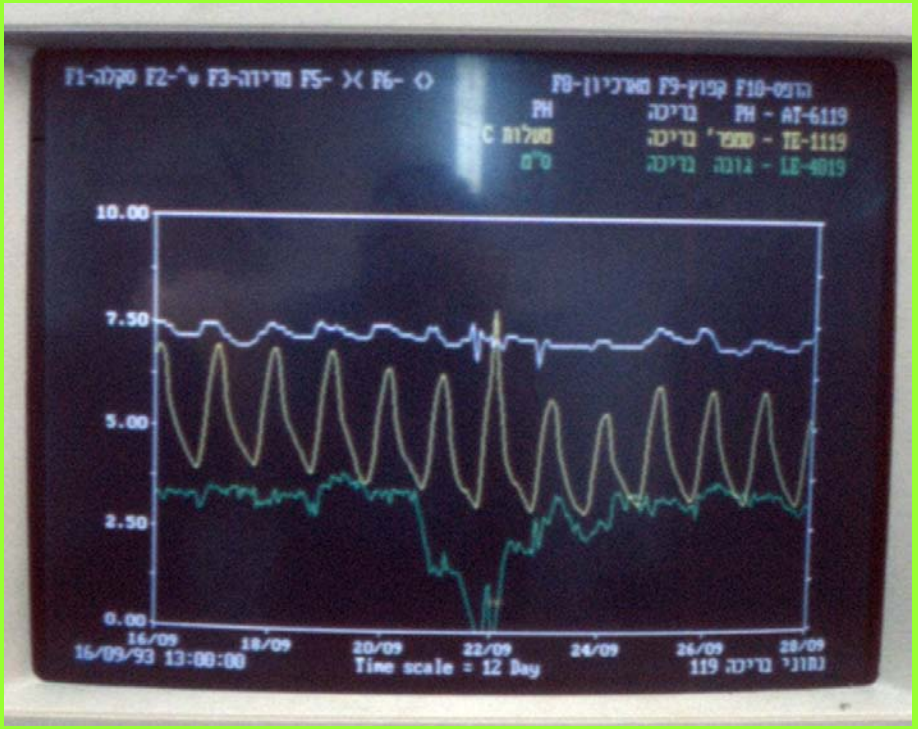
pH & Alkalinity Control

HCl & CO_2





pH Control, Depth, Temp recording history



Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

- **Area layout**
- **Pond design**
- **Oblong raceways [length (10-300m), width (1-20m)]**
- **Optimal size area (300-4,000m^2)**
- **Distal end, hydraulic radius**
- **Ground infrastructure (area preparation)**
- **Pond lining (none, clay, concert, asphalt, fiberglass, plastic sheeting, others)**
- **Liquid flow (paddle wheels, pumps, airlift, moving board, others)**
- **Paddle wheel**
- **Outside walls and channel dividers**
- **Flow velocity (laminar liquid flow velocity, 5-40 cm/sec)**
- **Site control, pH control**
- **Carbonation**
- **Mixing & Turbulence**
- **Depth (5-100cm, depth control)**
- **Head loss, hydraulics, Manning's "n" values**
- **Pond accessories (drainage, cleaning, pumps, pipes)**

Mixing
by liquid flow velocity of ~0.5 ft./sec?

DESIGN OF GROWTH CHANNELS

Mixing:

Continuous mixing of algal cultures is required to prevent thermal stratification and to maintain carbonation. Previous research has shown that gentle mixing is best applied with paddle wheels and that a linear liquid velocity of about 0.4 to 0.5 ft. per second is usually sufficient to prevent thermal stratification and cell sedimentation. It is also of a magnitude to foster counter-current carbonation.

Because of a possible need to develop cultures on a semi batch as well as on a continuous basis, it has been decided to develop 10 one-acre units. These units will be on a flat surface.

In the following we will develop design parameters on one unit. To do so, it is necessary initially to decide on the unit's length and width.

Flow, Mixing or Turbulence?

Key Factors for High Productivity

(both channels at 30cm/sec)

Mixing

O_2 and CO_2

O_2 super saturation?

(Nurdogan & Oswald, 1983)

TABLE 15

Effect of Mixing on Carbon Dioxide and Oxygen Mass Transfer (pH 7.8)(1)

	nanomoles cm^{-2} sec^{-1} $atmos^{-1}$	
	oxygen	carbon dioxide
Still Water	0.01	7.8(2)
Mixed Water	0.15	9.2

(1) Wood, K.C. "Carbon Doxide Diffusivity Across the Air-water Interface," Archives of Hydrobiology, 73:57-69, 1967.

(2) Calculated, other data is experimental.

Biology & Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

- **Area layout**
- **Pond design**
- **Oblong raceways [length (10-300m), width (1-20m)]**
- **Optimal size area (300-4,000m^2)**
- **Distal end, hydraulic radius**
- **Ground infrastructure (area preparation)**
- **Pond lining (none, clay, concert, asphalt, fiberglass, plastic sheeting, others)**
- **Liquid flow (paddle wheels, pumps, airlift, moving board, others)**
- **Paddle wheel**
- **Outside walls and channel dividers**
- **Flow velocity (laminar liquid flow velocity, 5-40 cm/sec)**
- **Site control, pH control**
- **Carbonation**
- **Mixing & Turbulence**
- **Depth (5-100cm, depth control)**
- **Head loss, hydraulics, Manning's "n" values**
- **Pond accessories (drainage, cleaning, pumps, pipes)**

Head Loss & Depth at 0.5 ft/sec

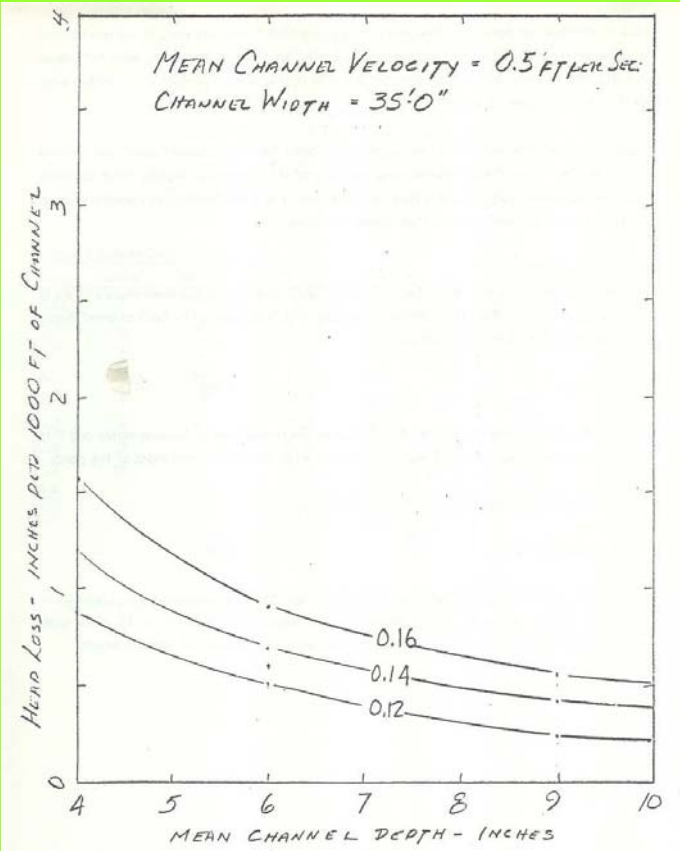
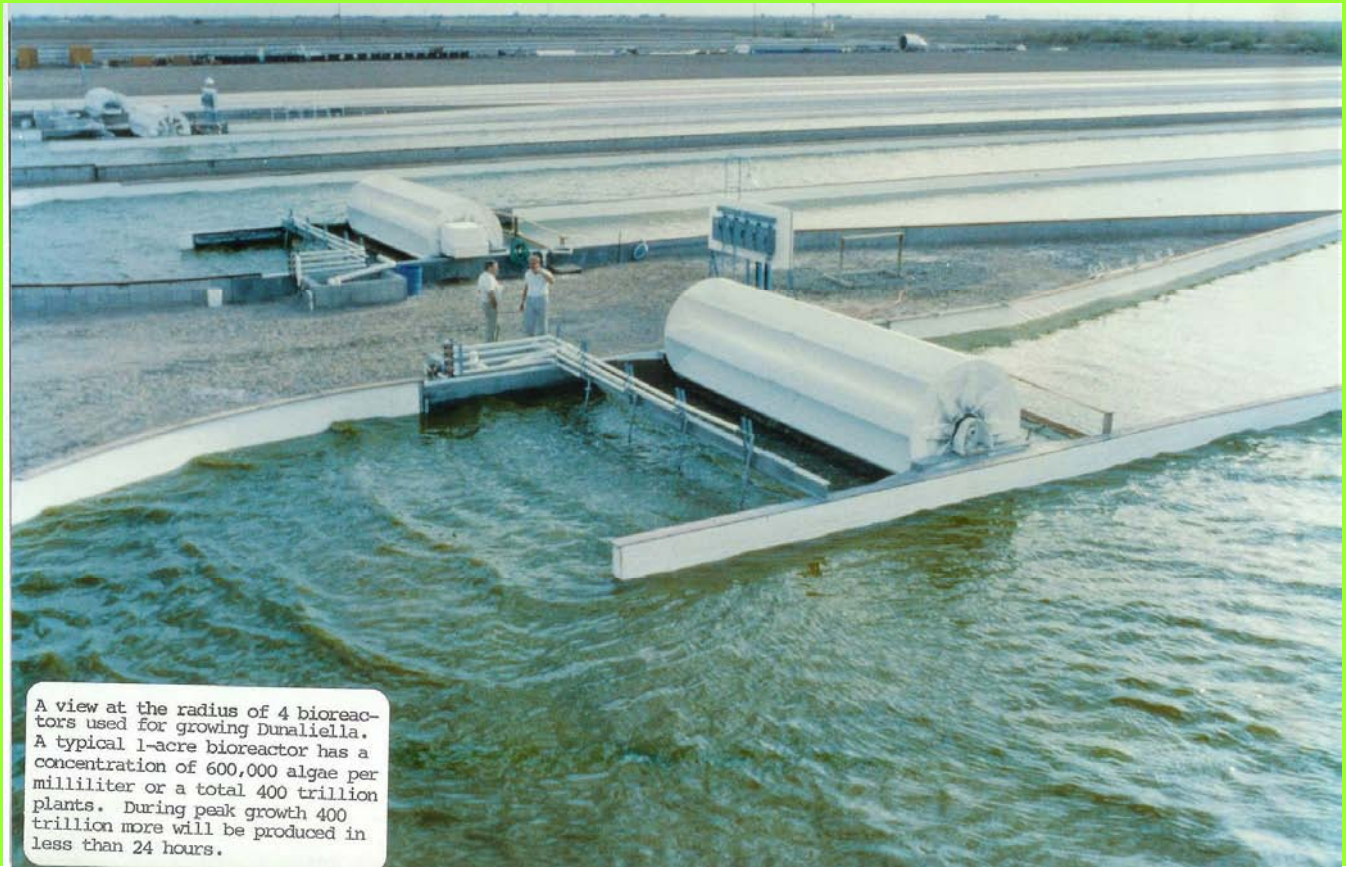


FIGURE 19. HEAD LOSS AT 0.5 FT PER SECOND FOR INDICATED "n" INCHES PER 1000 FT OF CHANNEL LENGTH.

"n" inches/1,000ft channel length

Oswald's Pond Design, 1983



Biology & Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

- **Area layout**
- **Pond design**
- **Oblong raceways [length (10-300m), width (1-20m)]**
- **Optimal size area (300-4,000m^2)**
- **Distal end, hydraulic radius**
- **Ground infrastructure (area preparation)**
- **Pond lining (none, clay, concert, asphalt, fiberglass, plastic sheeting, others)**
- **Liquid flow (paddle wheels, pumps, airlift, moving board, others)**
- **Paddle wheel**
- **Outside walls and channel dividers**
- **Flow velocity (laminar liquid flow velocity, 5-40 cm/sec)**
- **Site control, pH control**
- **Carbonation**
- **Mixing & Turbulence**
- **Depth (5-100cm, depth control)**
- **Head loss, hydraulics, Manning's "n" values**
- **Pond accessories (drainage, cleaning, pumps, pipes)**

Pond Cleaning
Machine use: fast, simple, efficient

Location? (Oswald 1983)
Light & Temperature, Winter & Summer

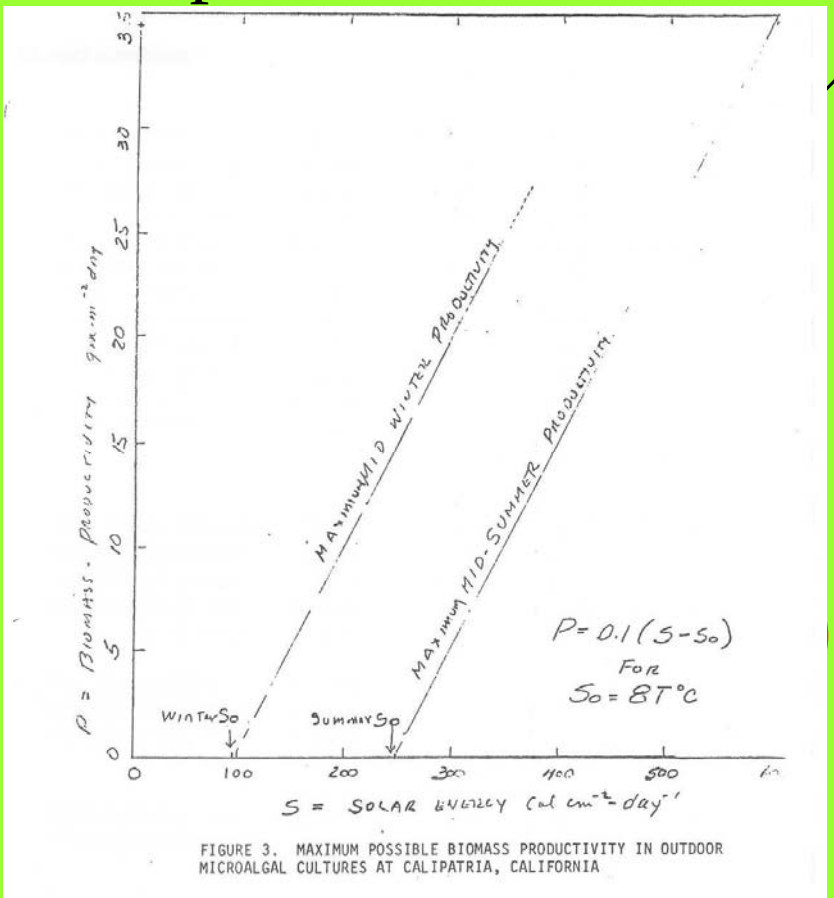


FIGURE 3. MAXIMUM POSSIBLE BIOMASS PRODUCTIVITY IN OUTDOOR MICROALGAL CULTURES AT CALIPATRIA, CALIFORNIA

Location?

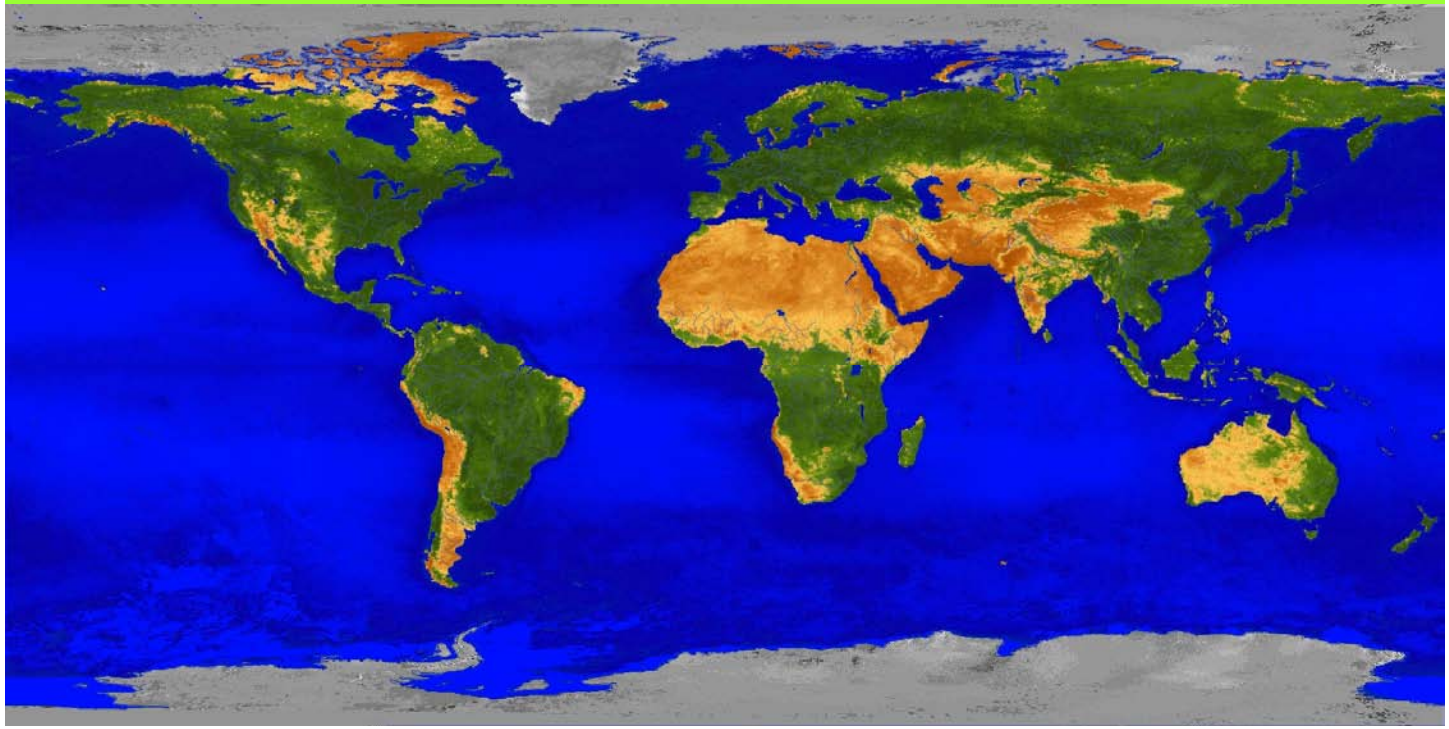
Climatic regions most suitable for microalgae :

annual average temperatures of > 15 °C” (Benemann, 2007)

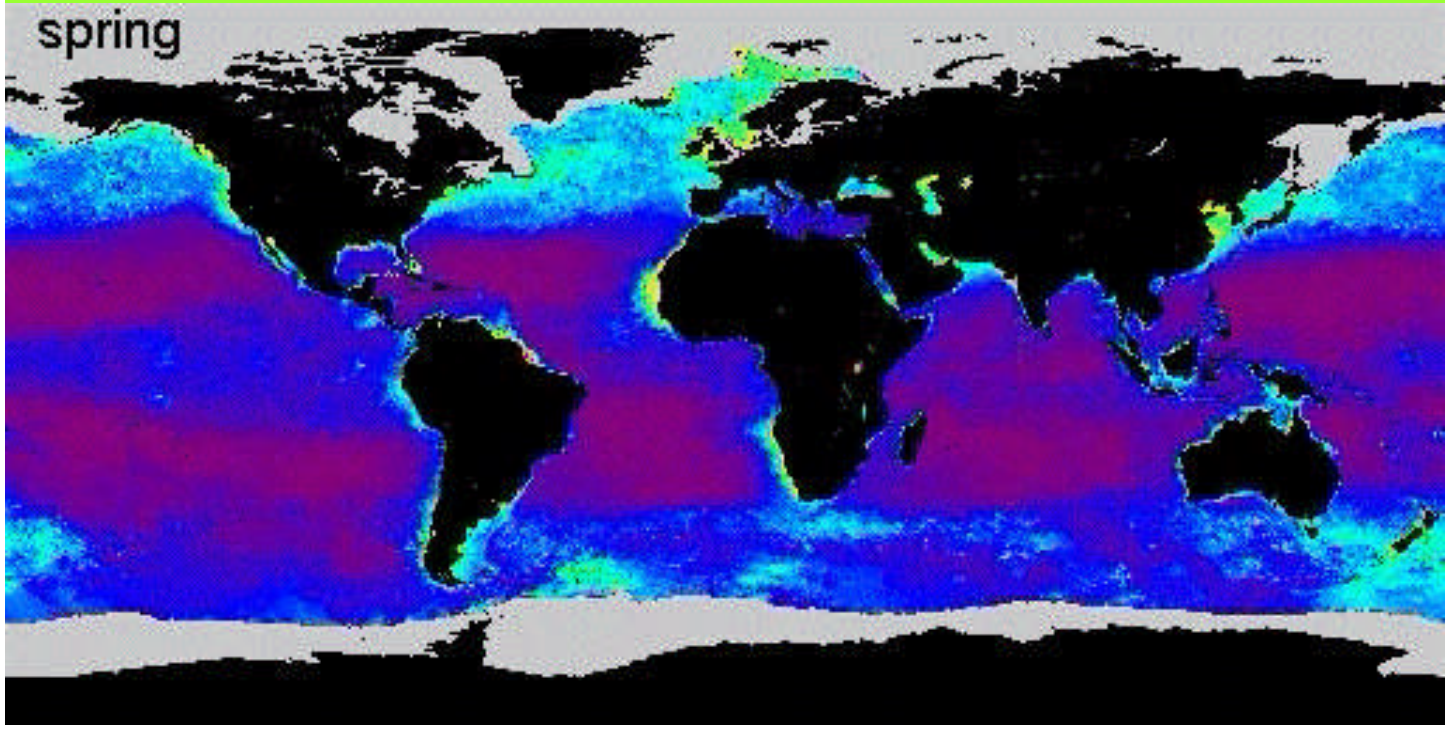
Optimal: 4-10 night °C, 10-22 day °C

Higher lipid Content

Less contamination



Location?
Spring Conditions
low night temp, moderate day temp



Biology & Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

Oswald Design
25 years later

Biology & Bio-Engineering Requirements for Maximal Productivity in Algal Open Ponds

- **Location, same like higher plants**
- **Area layout, as available, preferred lower temperatures**
- **Pond design, raceways**
- **Oblong raceways [length (10-300m), width (1-20m)], 5m x 150m**
- **Optimal size area (300-4,000m^2), 1,500m^2 by one paddle**
- **Distal end, hydraulic radius, necessary**
- **Ground infrastructure (area preparation), at minimum cost**
- **Pond lining (none, clay, concert, asphalt, fiberglass, plastic sheeting, others), PE or PVC at low "n"**
- **Liquid flow (paddle wheels, pumps, airlift, moving board, others), paddle wheel (or?)**
- **Paddle wheel, XXXX?**
- **Outside walls and channel dividers, the cheapest (bricks, ground ramps)**
- **Flow velocity (laminar liquid flow velocity, 5-40 cm/sec), 30cm/sec ?**
- **Site control, pH control, essential**
- **Carbonation, 2-5 mM TDC at pH 7-8**
- **Mixing & Turbulence, important (why, how?)**
- **Depth (5-100cm, depth control), the minimum possible in large ponds**
- **Head loss, hydraulics, Manning's "n" values, low "n"**
- **Pond accessories (drainage, cleaning, pumps, pipes), essential**
- **Essentials at low cost: nutrients, CO_2, sea water (salt), electricity, energy**
- **Crop protection**

Photosynthetic Limitation of Long Term Algal Productivity

Max Theoretical Algal Productivity

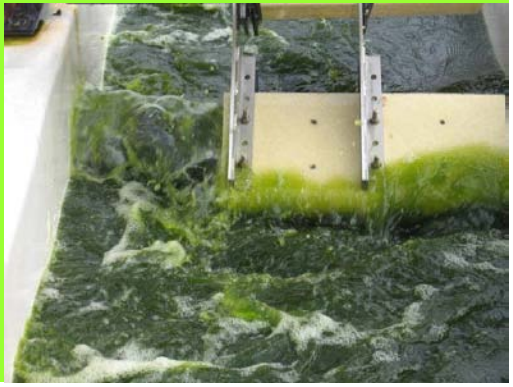
25 g/m^2/day

Environment Factor	Reduction	(%)
Solar light	-------	100
Scattering and reflecting properties of surface	10%	90
Absorption spectrum (depth of culture)	**50%**	**45**
Photosynthetic efficiency (25%)	75%	11.3
Light saturation (7-95%)	60%	4.5
Respiration, photo-respiration, excretion	5%	4.3
Photo-inhibition	10%	3.8
Temperature	20%	3.1
==========	==========	
	Productivity	
Mean daily solar intensity	4,000 kcal/m^2/day	
Energy productivity at 3% efficiency	120 kcal/m^2/day	
Algal biomass productivity (5 kcal/g)	**25 g/m^2/day**	
Higher Plants Max (sugar cane, corn, wheat, etc.)	**5 g/m^2/day**	

The Israel Electric Co/Seambiotic Ltd. Pilot Plant, Israel

The Israel Electric Co/Seambiotic Ltd. Pilot Plant, Israel

Low Cost Production of marine *Nannochloropsis* at yearly average 20g biomass/m^2/day (~ 30% lipids)



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