NREL-AFOSR Workshop, Algal Oil for Jet Fuel Production, Arlington, VA February 19th, 2008

Overview:

Algae Oil to Biofuels

(annotated presentation)

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Abstract – a short history of algae biofuels

- Microalgae were first mass cultured on rooftop at MIT during the early 1950s, first mention of algae biofuels in report of that project.

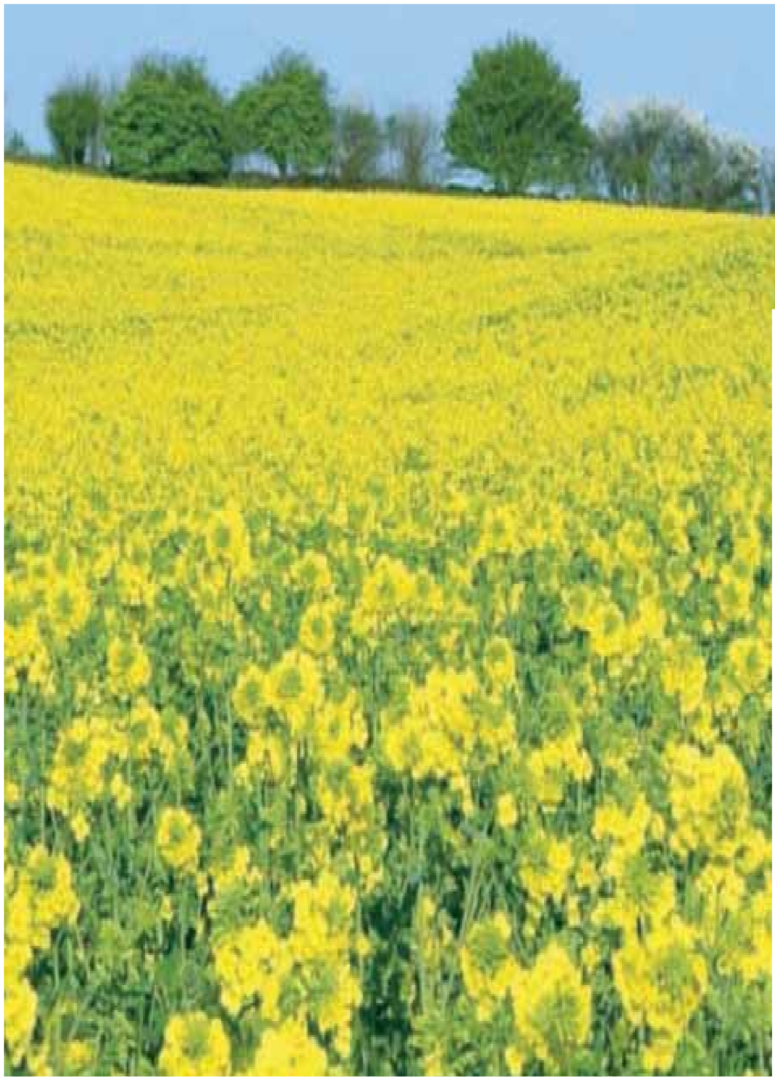
- Methane from algae studied at U.C. Berkeley during the 1950s, Initial conceptual process and systems analysis published 1960

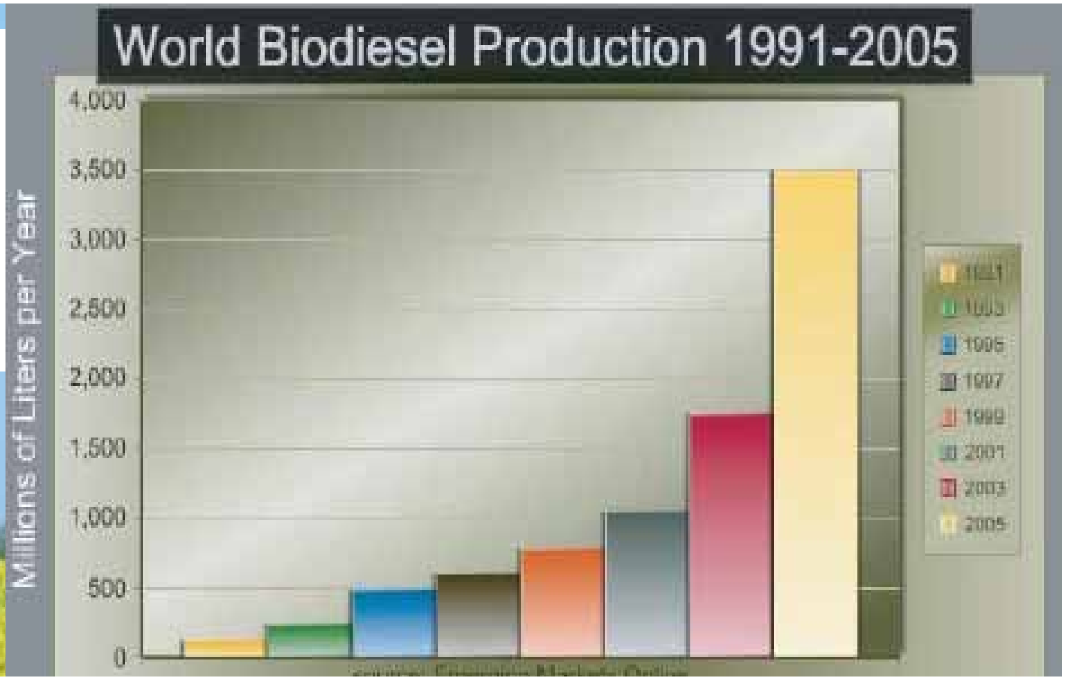
- The energy shocks of the 1970s led renewed study of microalgae biofuels, H2 and methane in combination with wastewater treatment

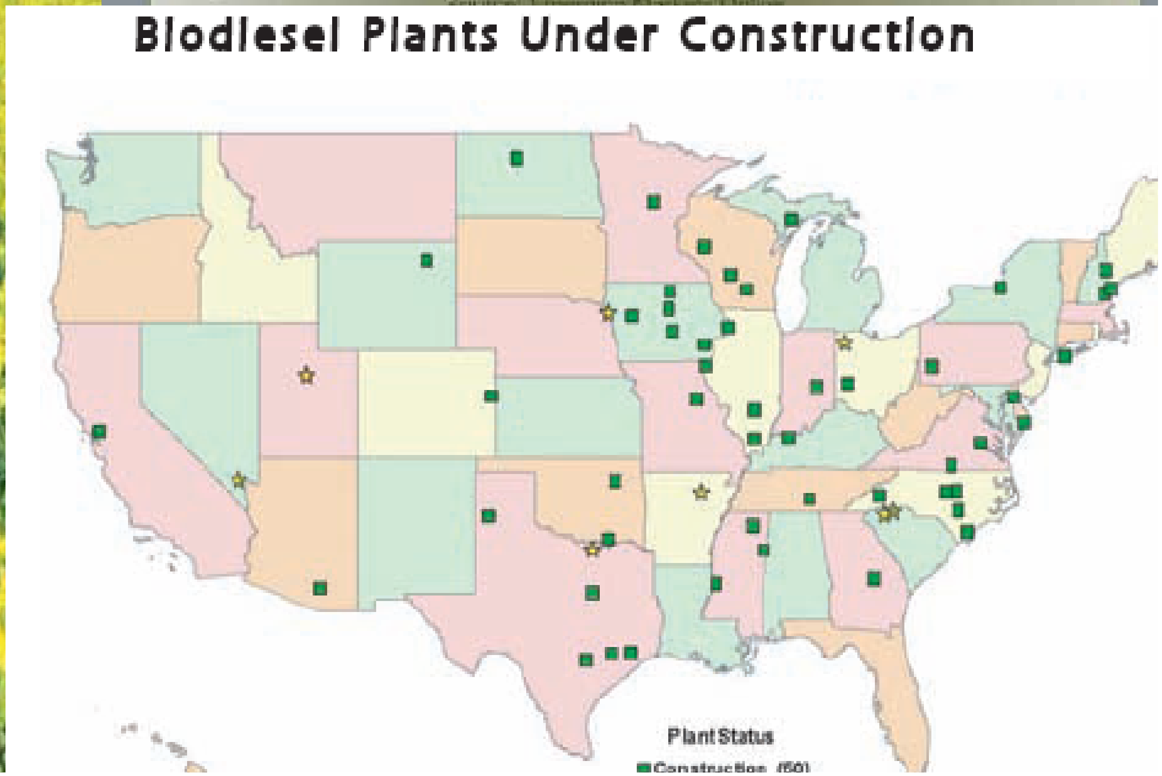
- From 1980 to 1995, the U.S. DOE-NREL ASP for microalgae oil production. Initial issue: open ponds vs. closed photobioreactors The ASP culminated in open pond pilot plant at Roswell, New Mexico

- Algae oil production is still a long-term R&D goal. Like the ASP a future program should be an open collaboration by researchers from academia, national laboratories and industry, not inhibited by concerns about IP or commercial interests.

Not enough vegetable oil available. Biodiesel plants now at ~25% capacity, → need new sources





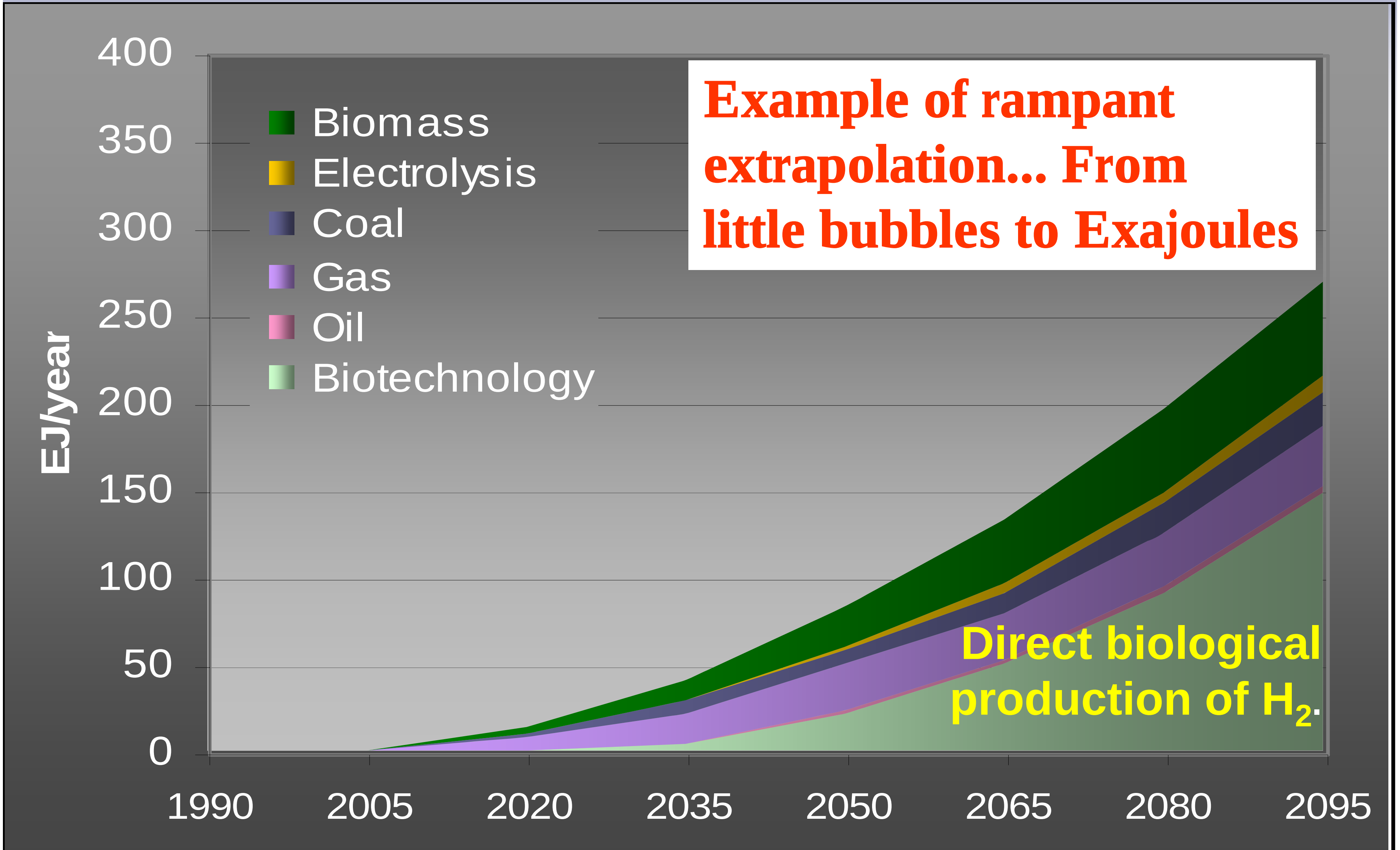


NYT 1/31/07: "Once a Dream Fuel, Palm Oil May Be an Eco-Nightmare"

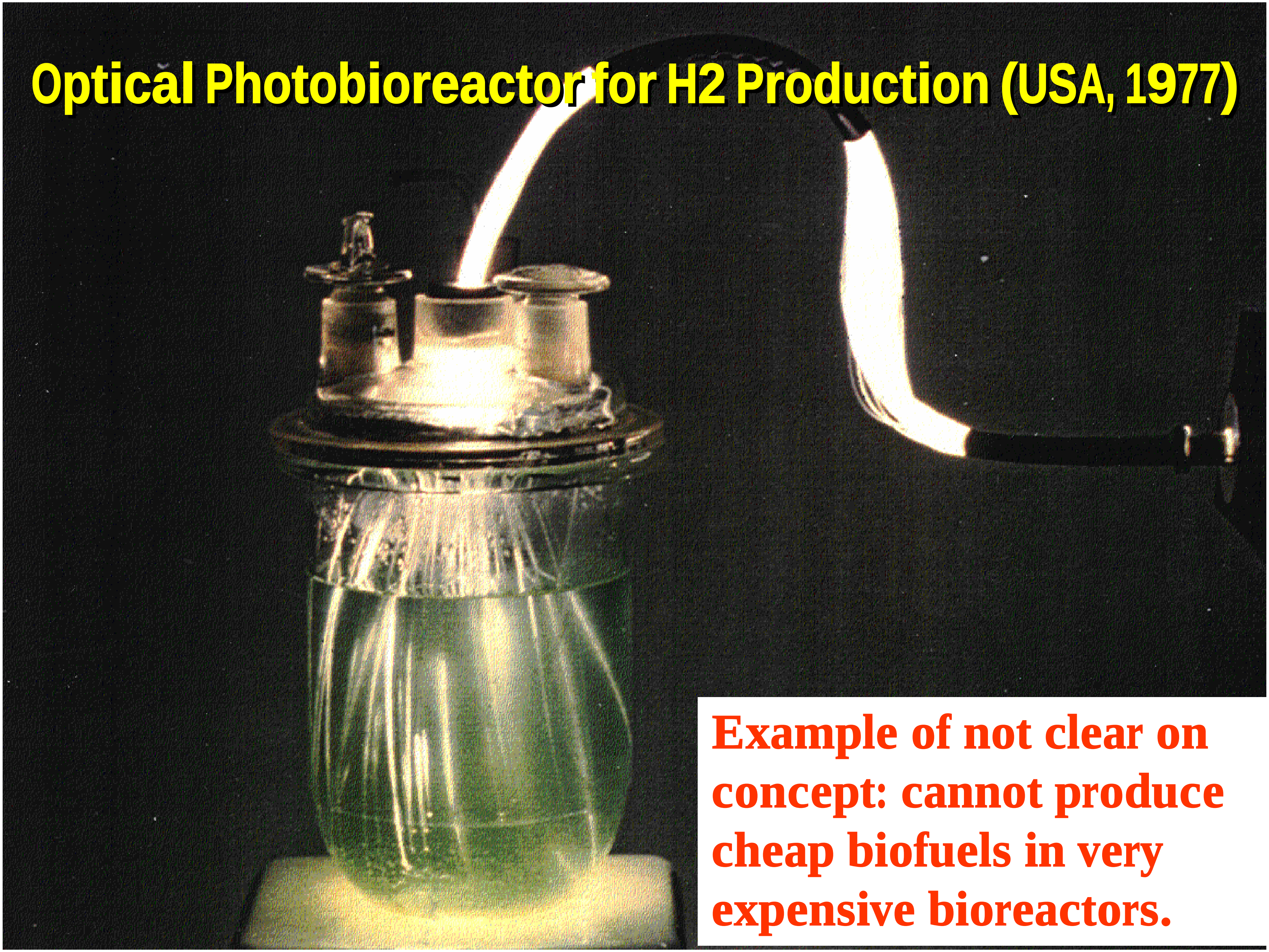

trends in
BIOTECHNOLOGY
Bubbles are H2 →
Microalgae:
a source of energy

Microalgae biotech could be a huge source of H_2 fuel

Jae Edmonds, World Industrial Biotech Congress, 2004



Optical Photobioreactor for H2 Production (USA, 1977)

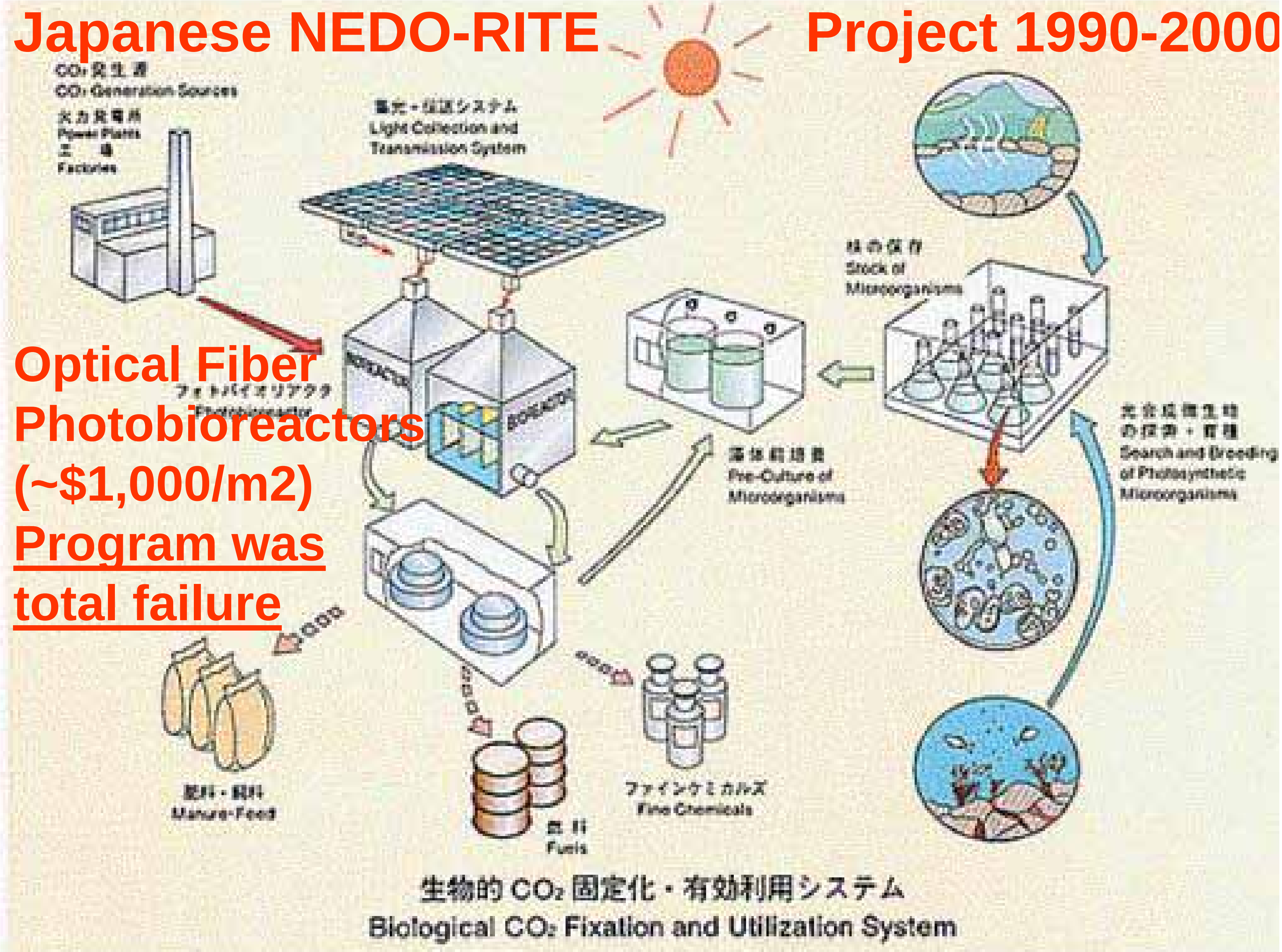


Example of not clear on concept: cannot produce cheap biofuels in very expensive bioreactors.

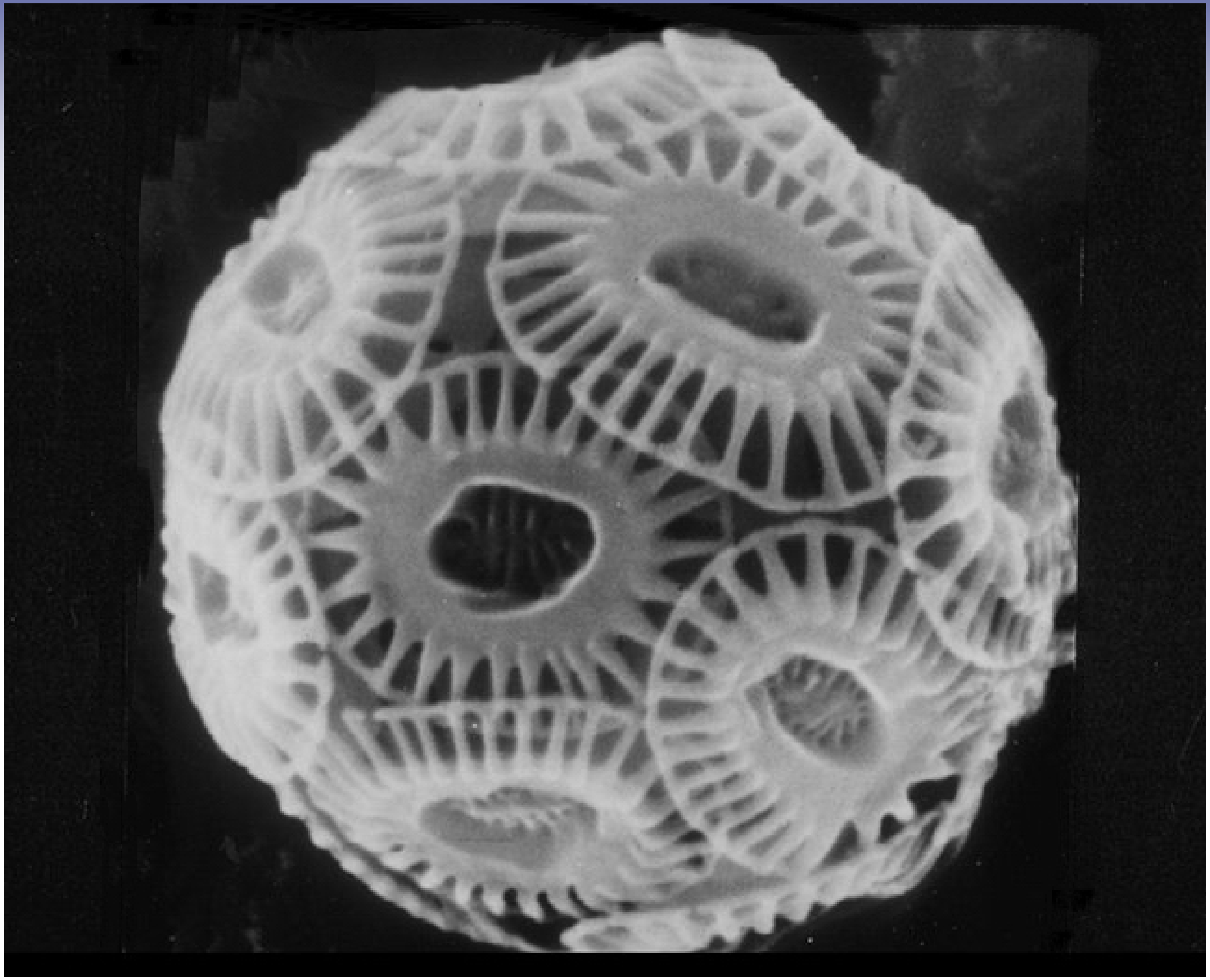
Japanese NEDO-RITE Project 1990-2000

Optical Fiber Photobioreactors (~$1,000/m2)

<u>Program was total failure</u>

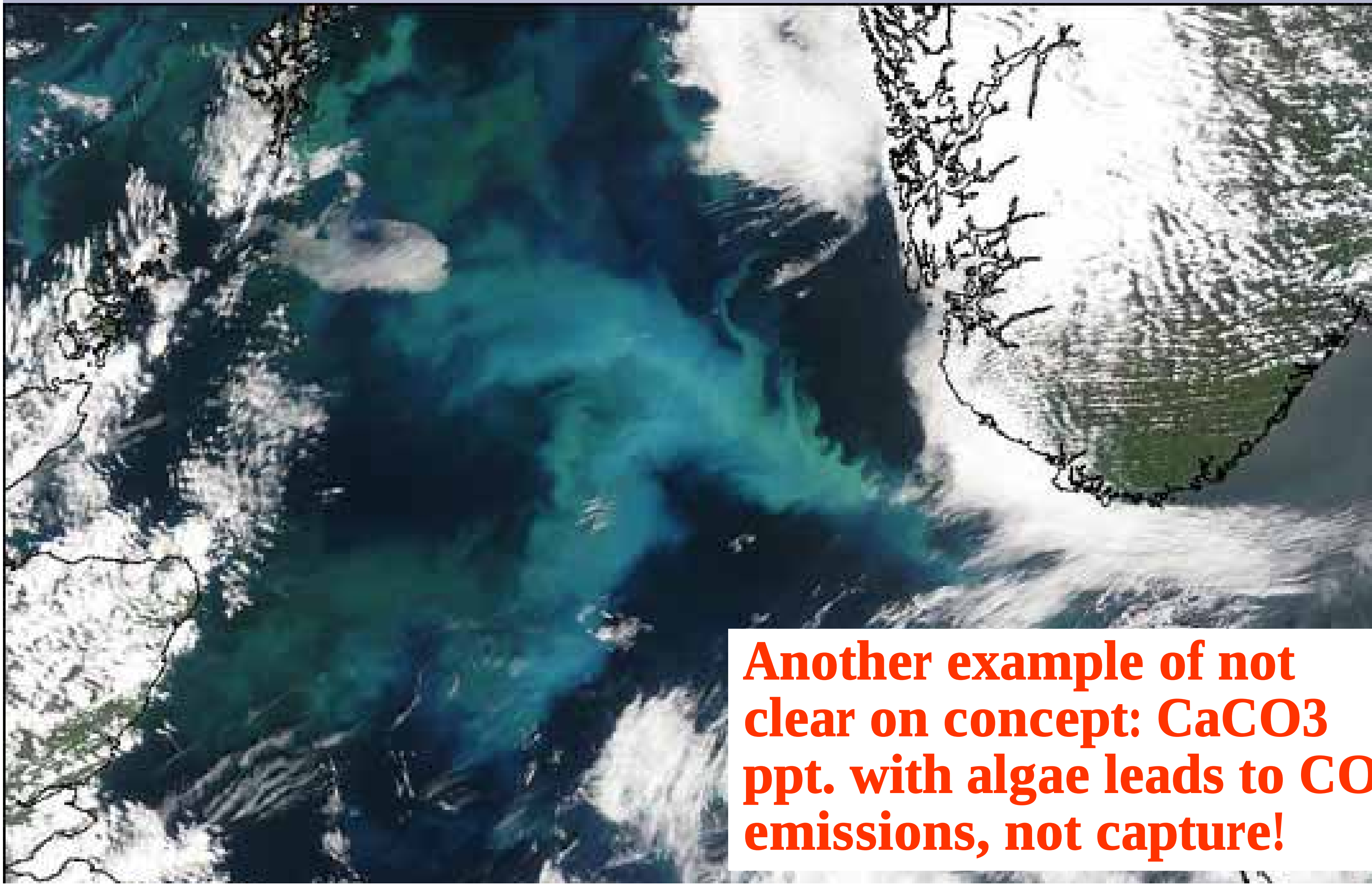


Microalgae for CO_2 Capture ? : *Emiliana huxleyi*



Many projects used these algae to abate CO_2 emissions

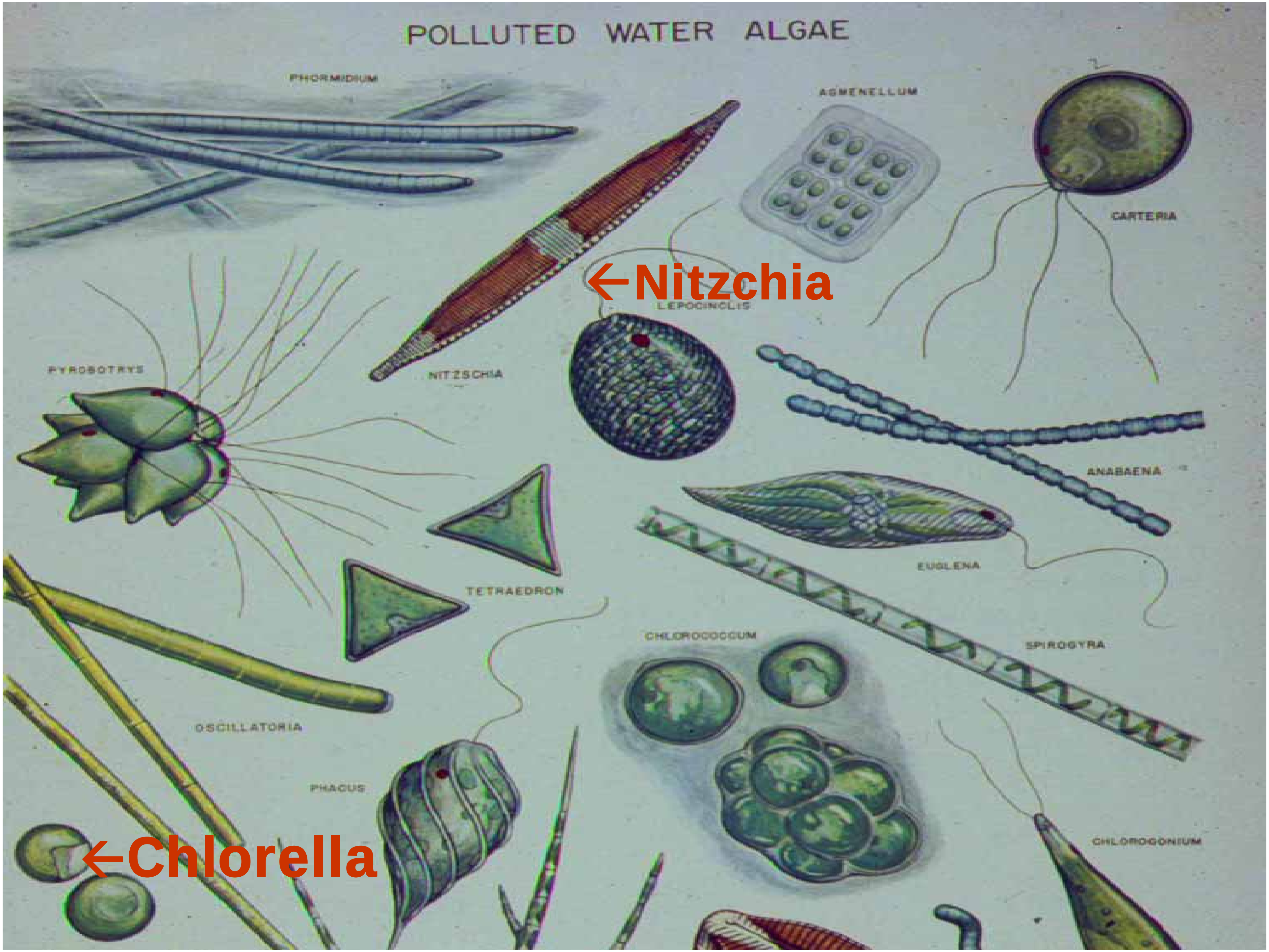
Large "whitening" in the Atlantic Ocean (due to coccolithophorids like E. huxleyi]



Another example of not clear on concept: $CaCO_3$ ppt. with algae leads to CO_2 emissions, not capture!

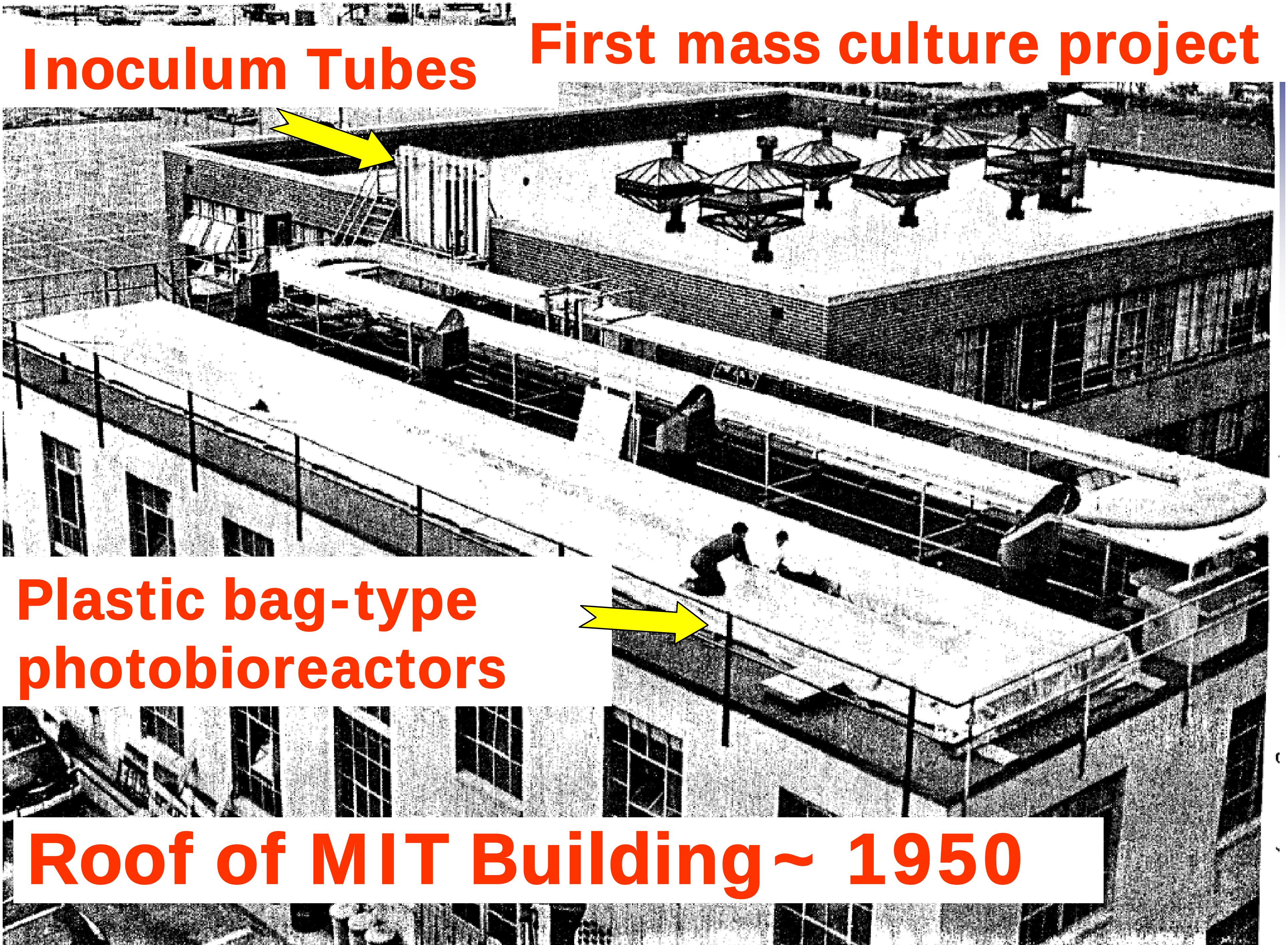
MICROALGAE DIVERSITY

- 30 000 described species (< 10% of estimated)
- 11 Divisions divided into 29 classes (vs. 2/12 vascular plants)



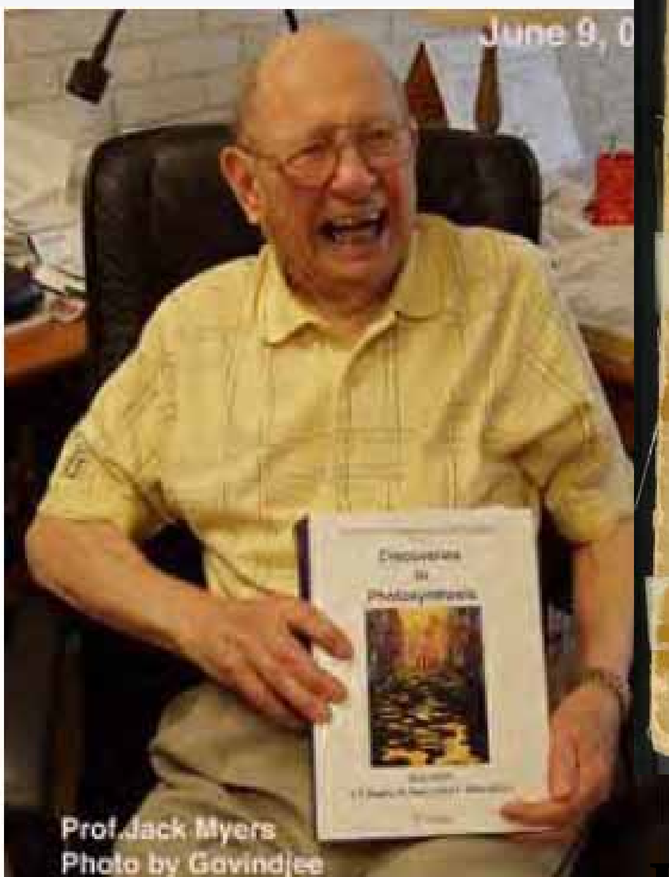
POLLUTED WATER ALGAE
PHORMIDIUM
AGMENELLUM
CARTERIA
←Nitzchia
LEPOCINCLIS
PYROBOTRYS
NITZSCHIA
ANABAENA
EUGLENA
TETRAEDRON
CHLOROCOCCUM
SPIROGYRA
OSCILLATORIA
PHACUS
CHLOROGONIUM
←Chlorella

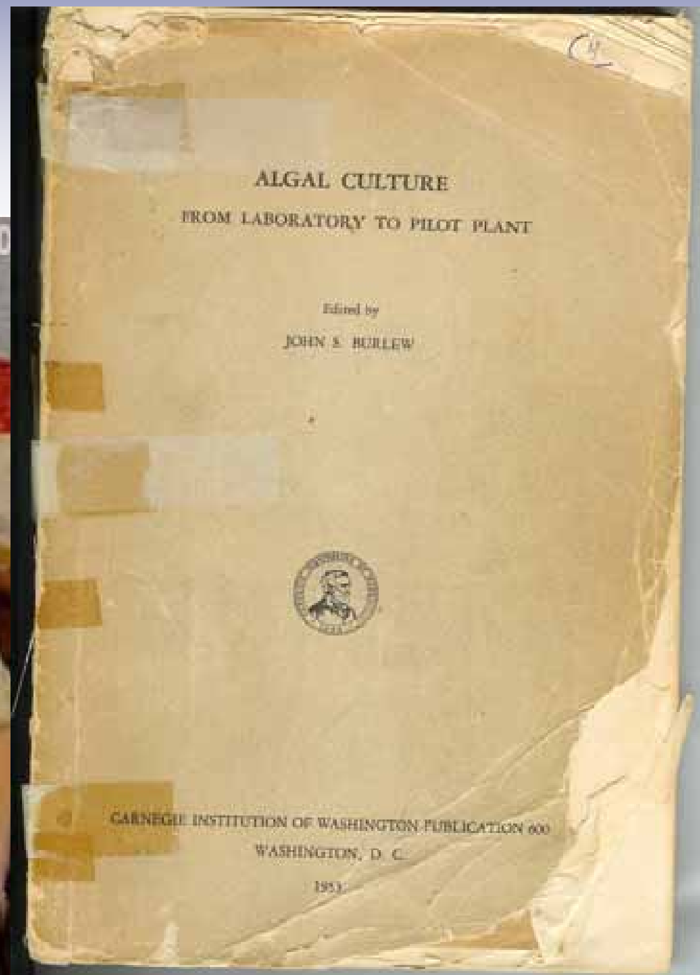
First mass culture project



Roof of MIT Building~ 1950

Jack Myers and Bessel Kok

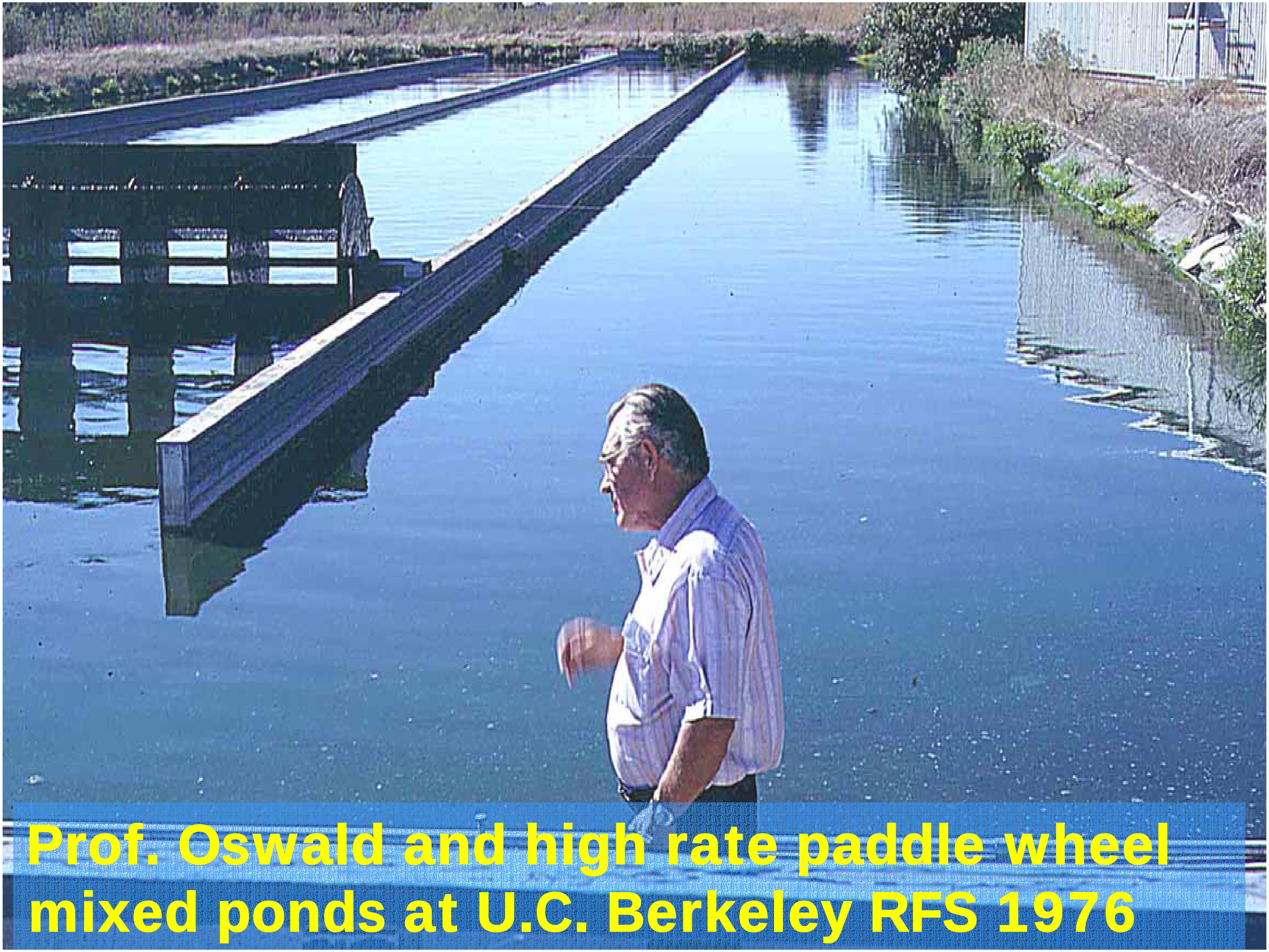




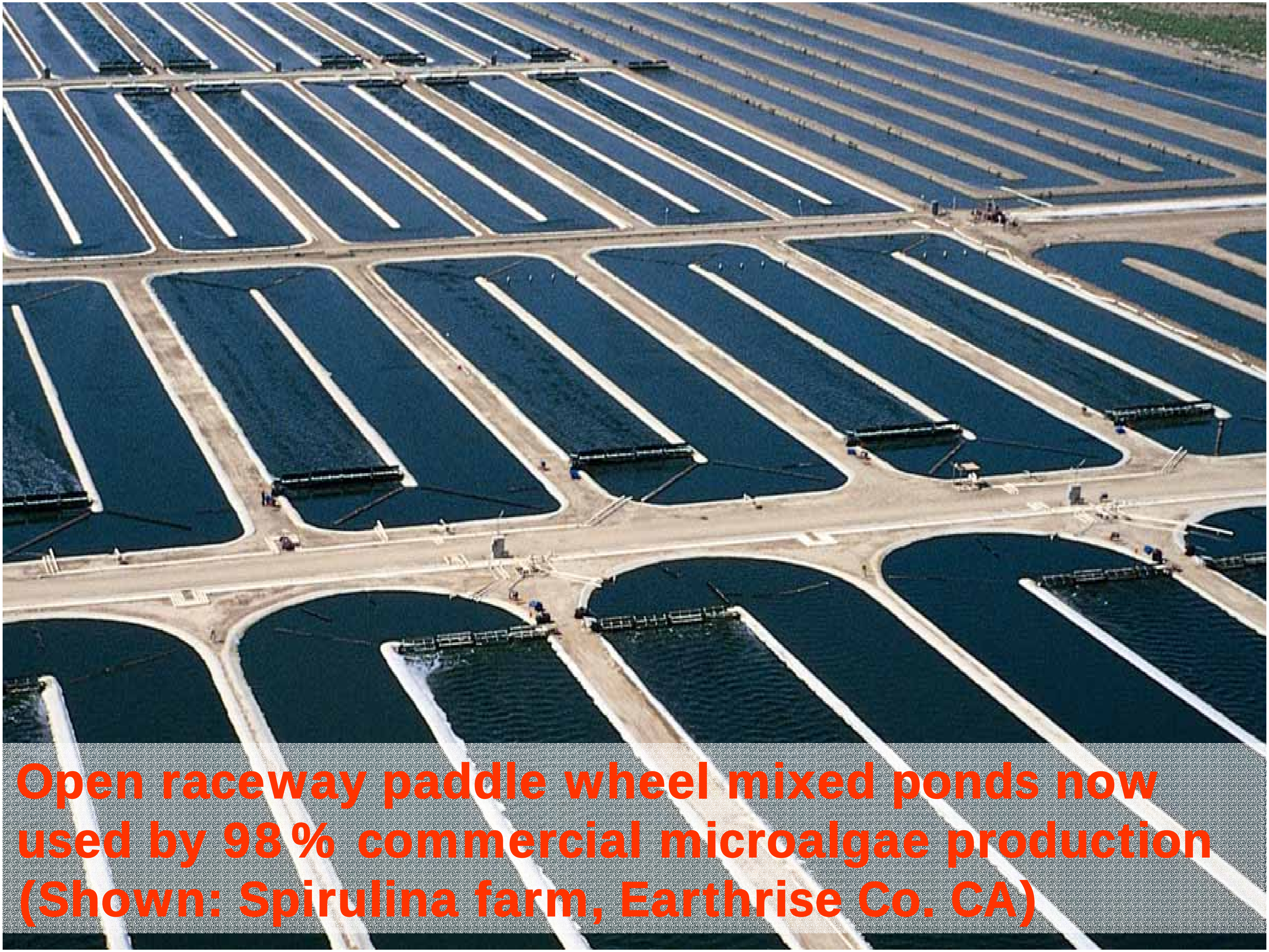
2006, Austin, Tx

Algae Culture from Laboratory to Pilot Plant (Burlew, 1953)

1956, Stanford U.



Prof. Oswald and high rate paddle wheel mixed ponds at U.C. Berkeley RFS 1976

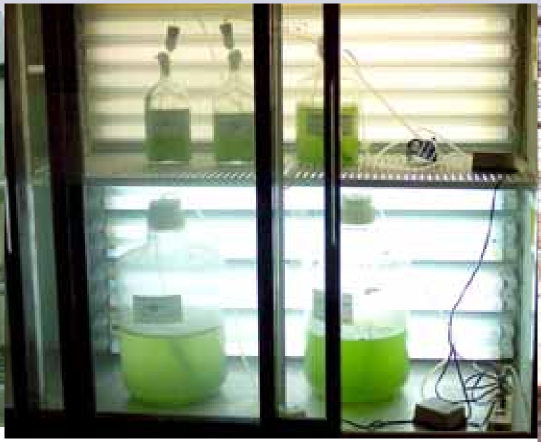


Open raceway paddle wheel mixed ponds now used by 98% commercial microalgae production (Shown: Spirulina farm, Earthrise Co. CA)

Arthrospira platensis (Spirulina)

Spirulina is easy to culture (high alkalinity medium and easy to harvest by screens

Spirulina Culture Expansion (Earthrise Farms)



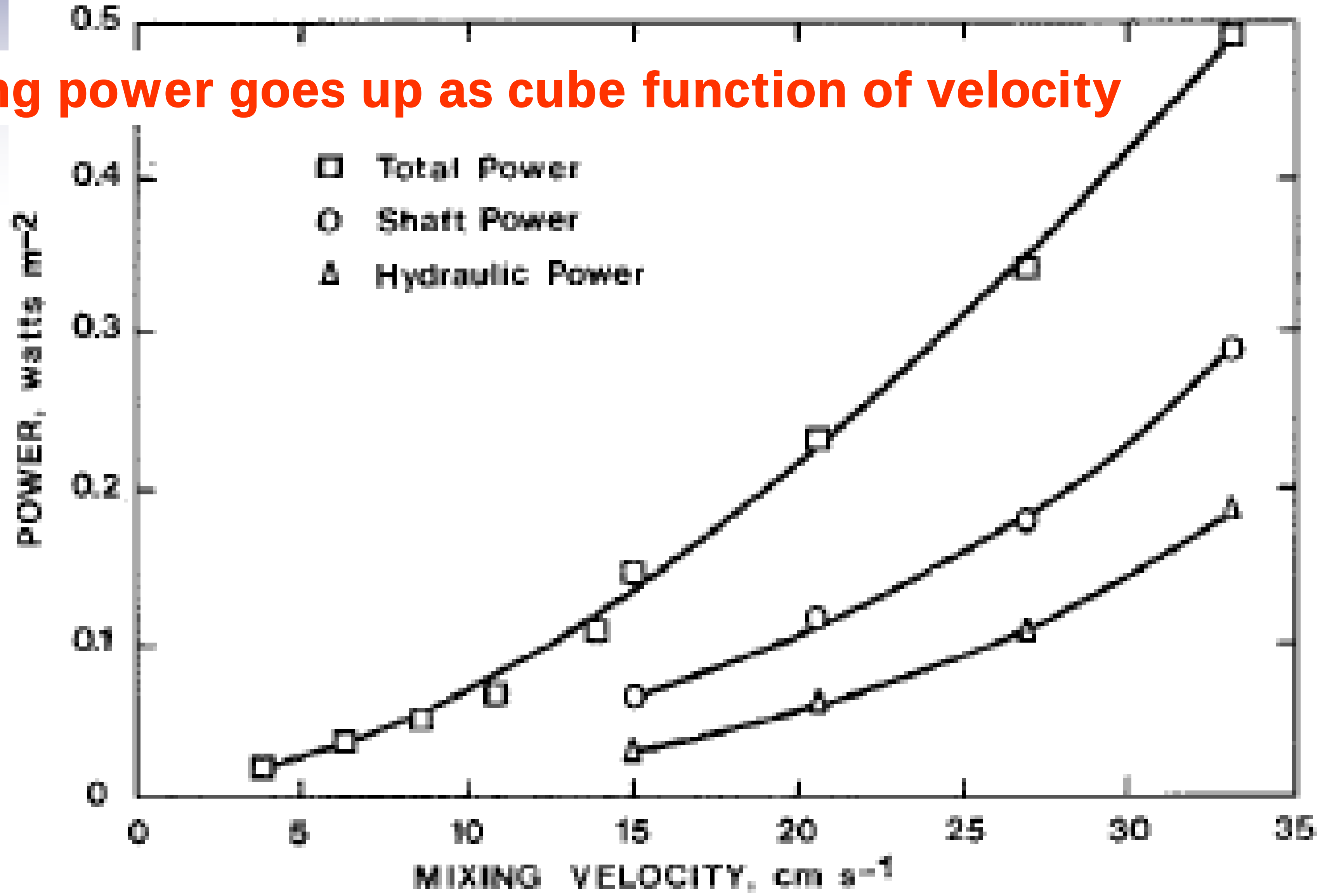
Spirulina Production in India
(Parry Nutraceuticals Ltd.)

Paddle wheels for mixing high rate ponds.

(Mixing at or below 30 cm / sec minimizes energy use)

Power required for mixing ponds

Mixing power goes up as cube function of velocity



Spirulina Production in China (Hainan]

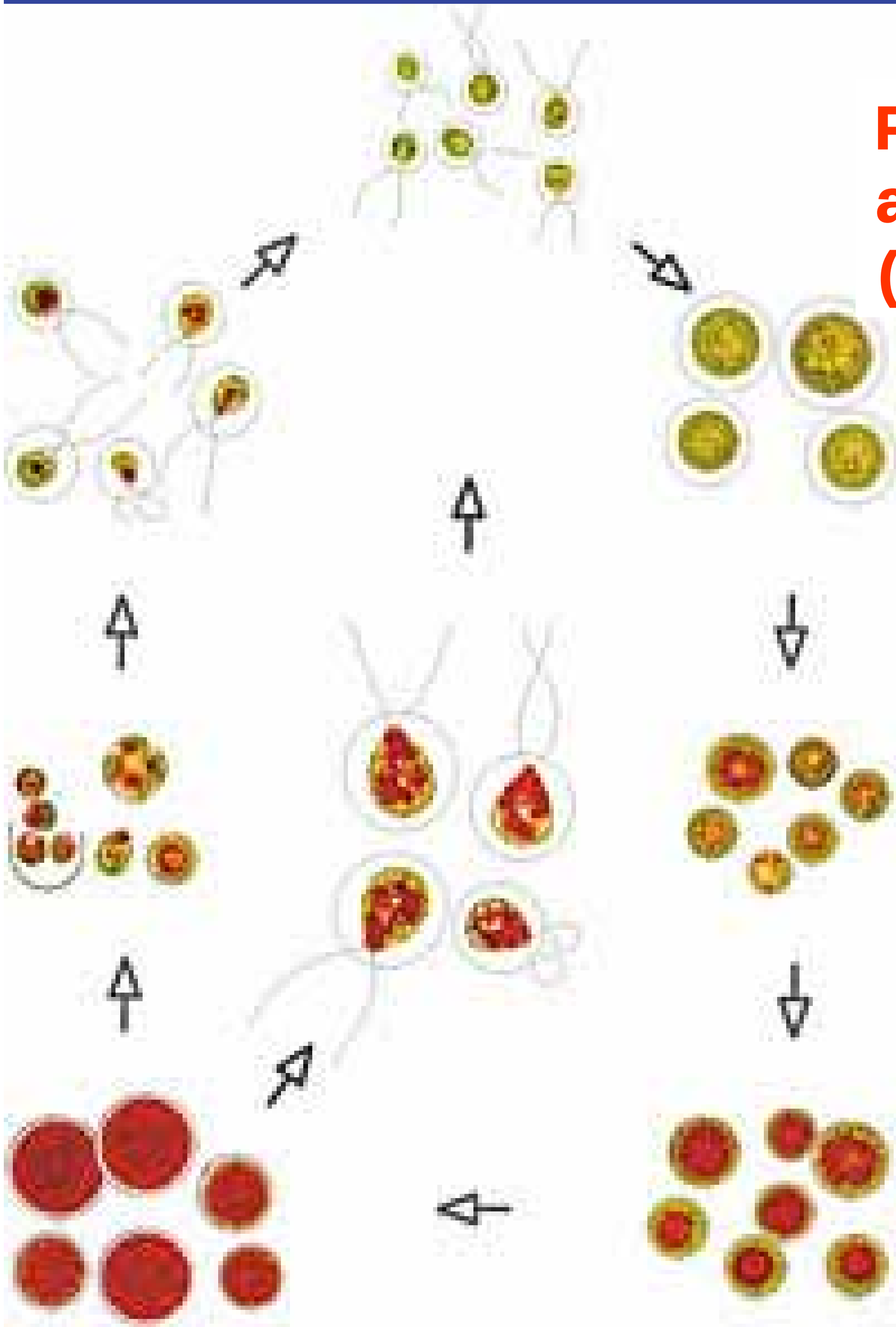
Current products from microalgae: nutraceuticals

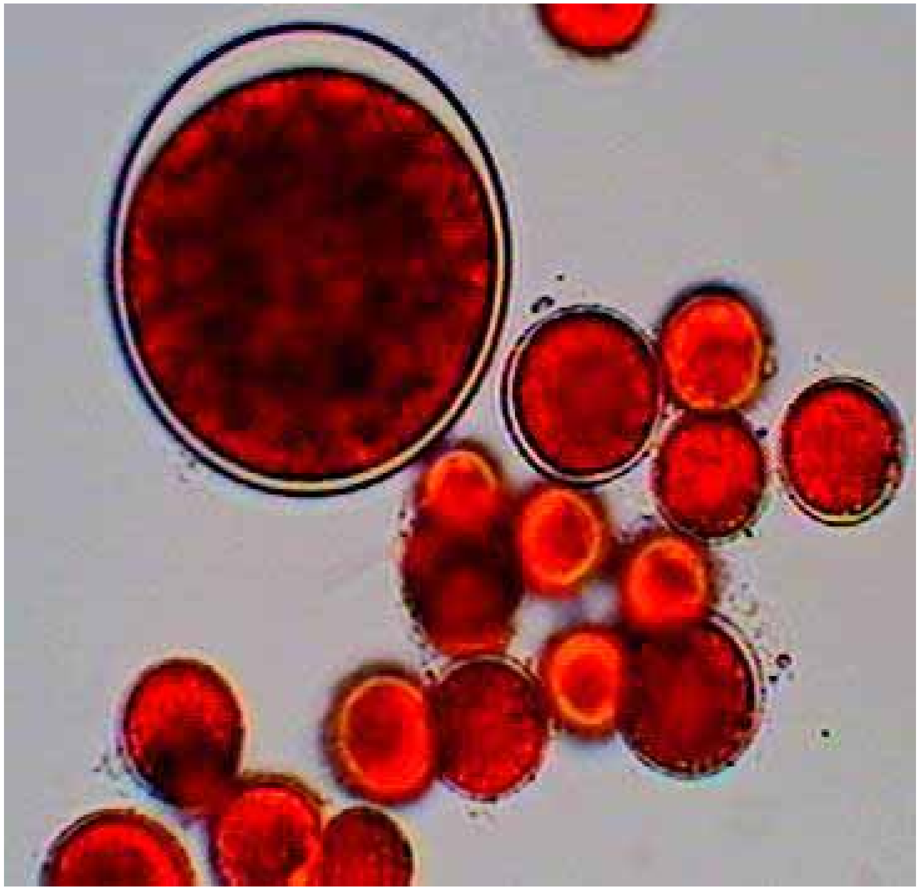
Spirulina and Haematococcus Ponds at Cyanotech Corp. in Hawaii

2 MW(e) Power Plant and CO2 Capture Tower at Cyanotech Corp., Hawaii

Haematococcus pluvialis

Production of red carotenoid astaxanthin, ~$10 million/ton (>$100,000/t algae biomass)





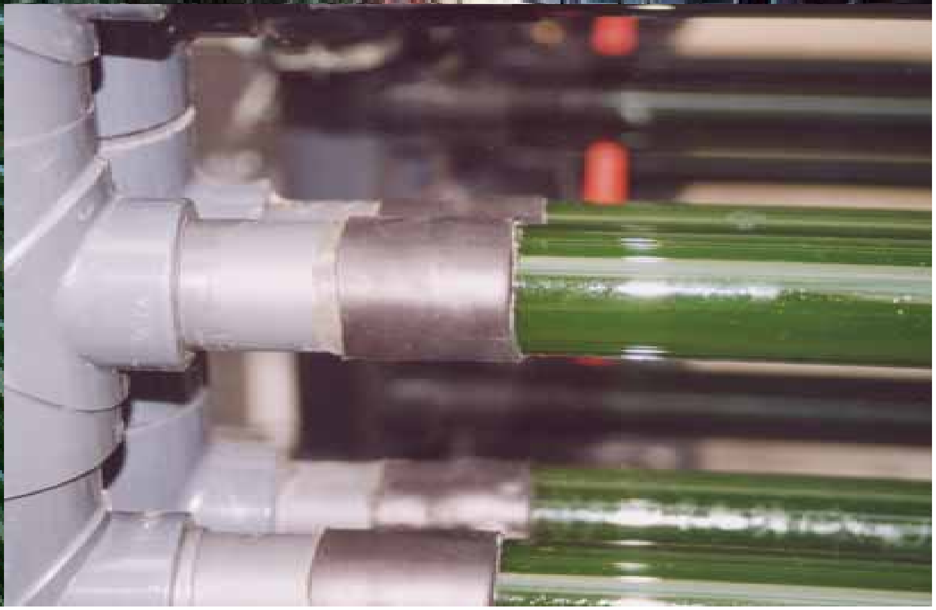
Haematococcus pluvialis production in Israel

These algae can be produced, and are, in open ponds, e.g. Cyanotech or in closed photobioreactors such as these. PBRs have advantages, but much more expensive (>10x)

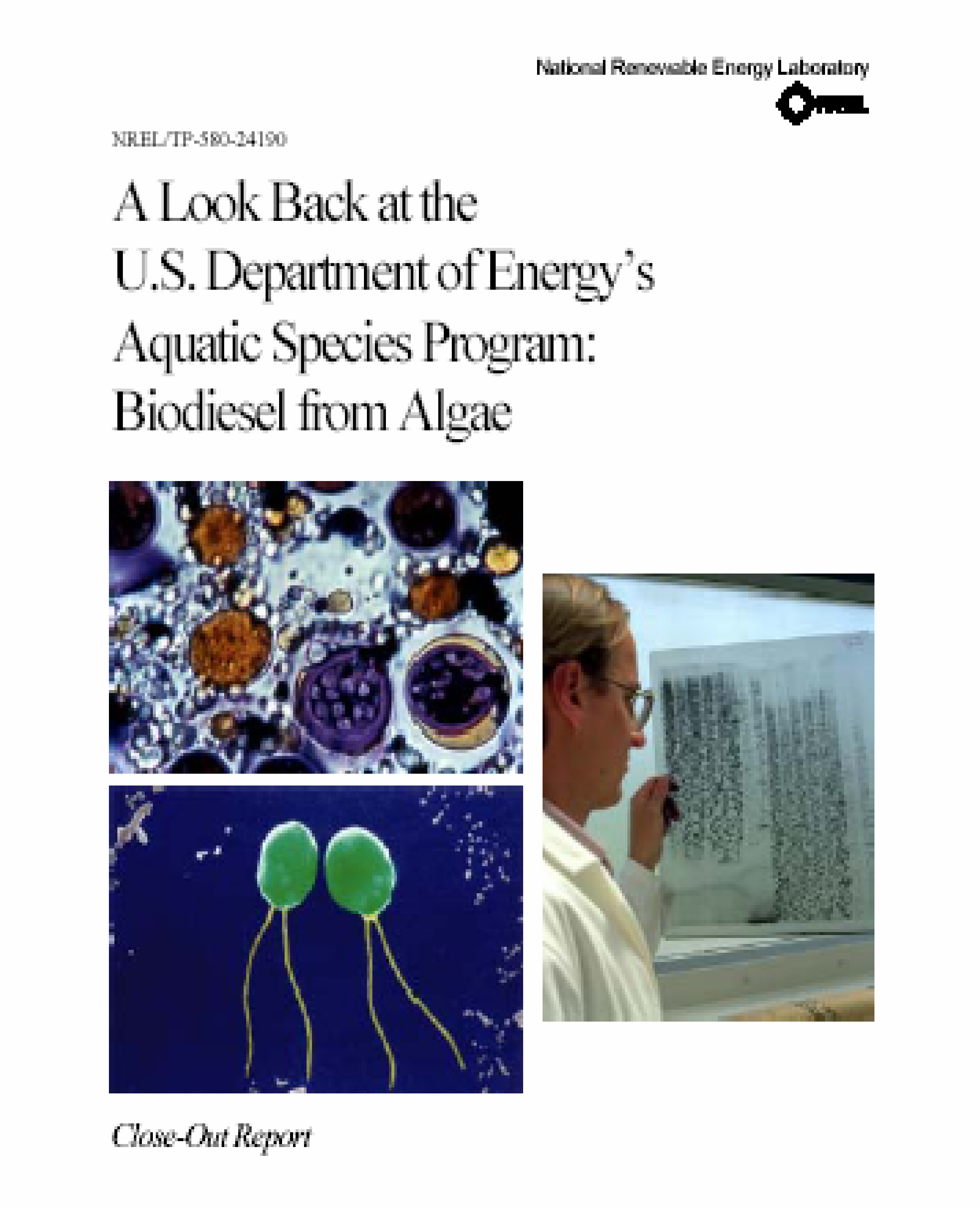
Most R&D is now on PBRs and several commercial systems established...

Commercial Photobioreactor in Germany

For Chlorella produciton.
Over $10million/hectare!
Went broke in short order




Commercial Photobioreactors in Spain (1989)
For Dunaliella pro
Operated for <2 w
before process fa



U.S. Dept. Energy Aquatic Species Program (ASP)

The ASP also started out with a PBR design as its amin initial focus.....

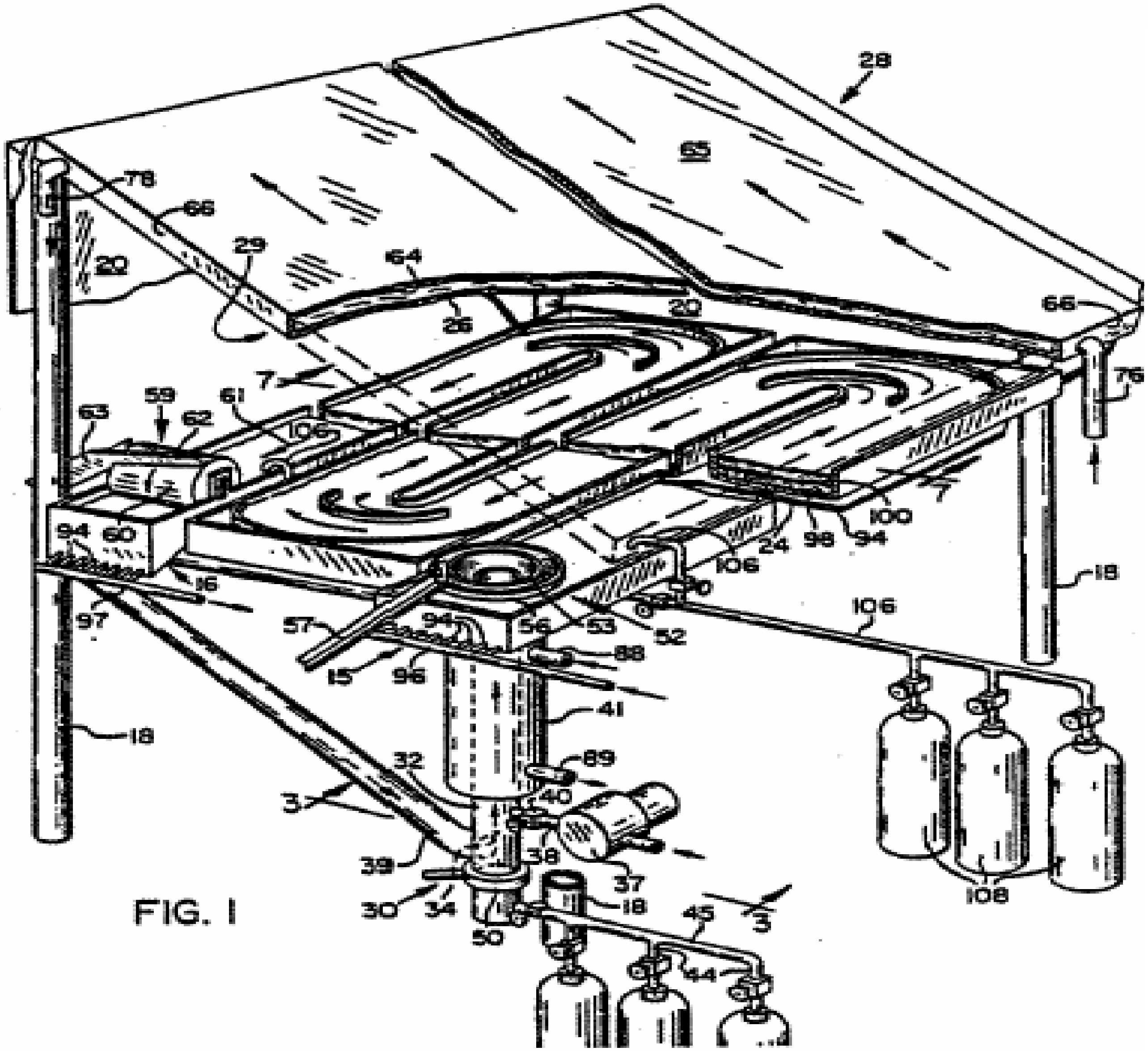


FIG. I

KEY PATENT CLAIMS

- GAS LIFT PUMP MECHANISM FOR CIRCULATION, CARBONATION AND HARVES
- HEAT EXCHANGE FOR TEMPERATURE CONTROL
- FOAM FRACTIONATION / SKIMMING HARVESTING
- $CaSO_4$ SOLUTION IN COVER TO REMOVE INHIBITING IR.
- MIXING TO ACHIEVE FLASHING LIGHT EFFECT

Patented closed PBR (L. Raymond 1st ASP PM)

Claims: very high yields >100t/ha-y, flashing light effect, oil content ~40%, etc.

Ed Laws at U. Hawaii showed not so. ASP then went to open ponds

Biotechnology and Bioengineering, Vol. 31, Pp. 336–344 (1988)

Photobioreactor Design: Mixing, Carbon Utilization, and Oxygen Accumulation

Joseph C. Weissman* and Raymond P. Goebel
Microbial Products, Inc. 408A Union Ave., Fairfield, California 94533

John R. Benemann
Department of Applied Biology, Georgia Institute of Technology, Atlanta,

Photobioreactor design and operation are discussed in terms of mixing, carbon utilization, and the accumulation of photosynthetically produced oxygen. The open raceway pond is the primary type of reactor considered; however small diameter (1–5 cm) horizontal glass tubular reactors are compared to ponds in several respects.

This paper written in response to many claims that closed photobioreactors were superior to open ponds. Pointed out some of the problems faced by both open ponds and closed PBRs.

Open Ponds vs. Closed Photobioreactors

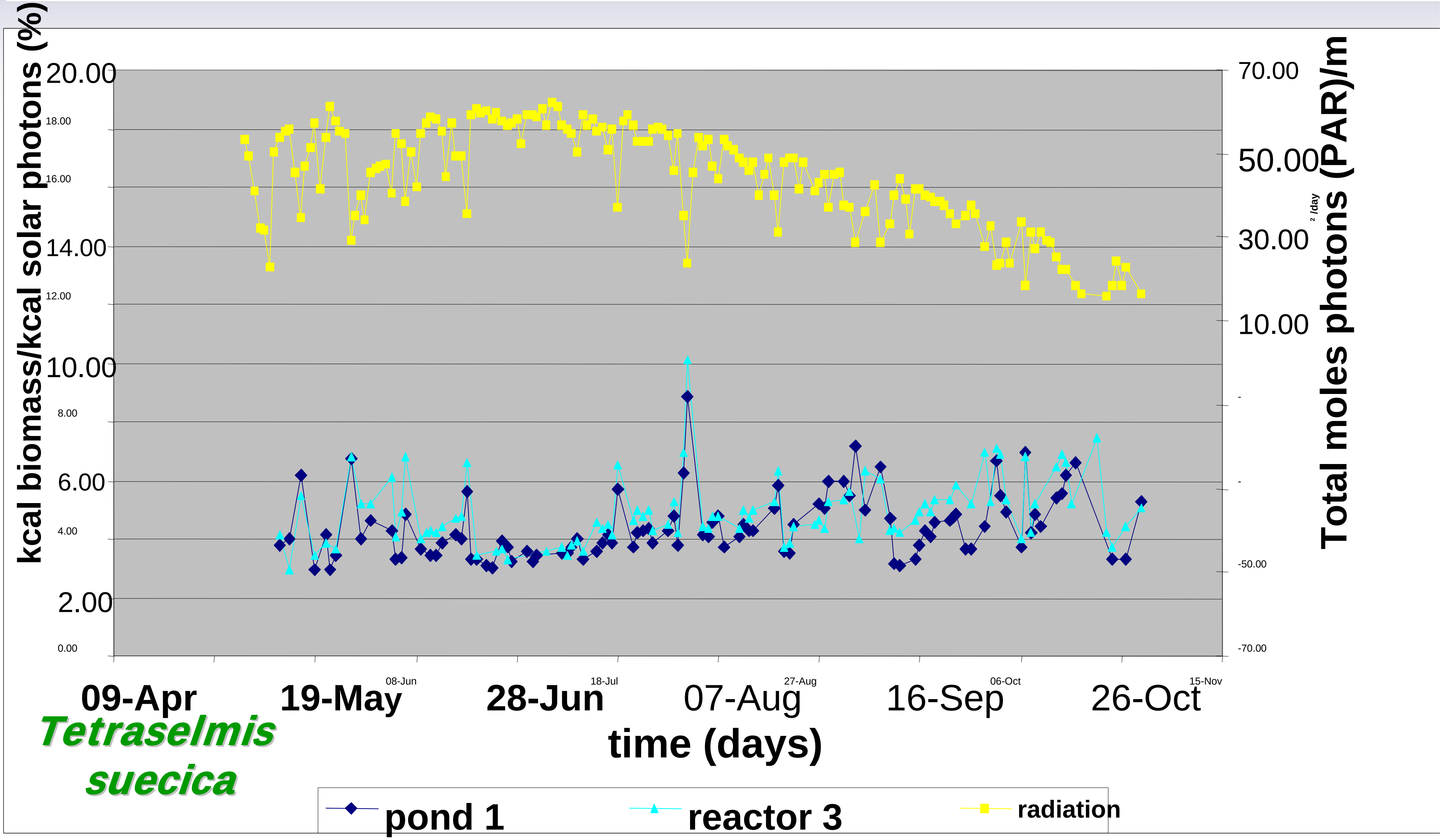
Parameter	Relative	Note
Contamination risk	Ponds > PBRs	Just a matter of time for either
Space required	Ponds ~ PBRs	A matter of productivity
Productivity	Ponds ~ PBRs	NO substantial difference except at low temperatures
Water losses	Ponds ~ PBRs	Evaporative cooling needed
CO_2 losses	Ponds ~ PBRs	Depends on pH, alkalinity, etc.
O_2 Inhibition	Ponds < PBRs	O_2 greater problem in PBRs
Process Control	Ponds ~ PBRs	no major differences (weather)
Biomass Concentration	Ponds < PBRs	function of depth, 2 -10 fold
Capital/Operating Costs	Ponds << PBRs	Ponds 10 -100 x lower cost!

CONCLUSION: Photobioreactors better than ponds? Sometimes but advantages way overstated. For biofuels can't afford PBRs

Eni Project (Monterotondo, Italy)
Compared PBRs & ponds using flue gas CO2

Photosynthetic Efficiencies in the Ponds and Photobioreactors (30% dilution/day)

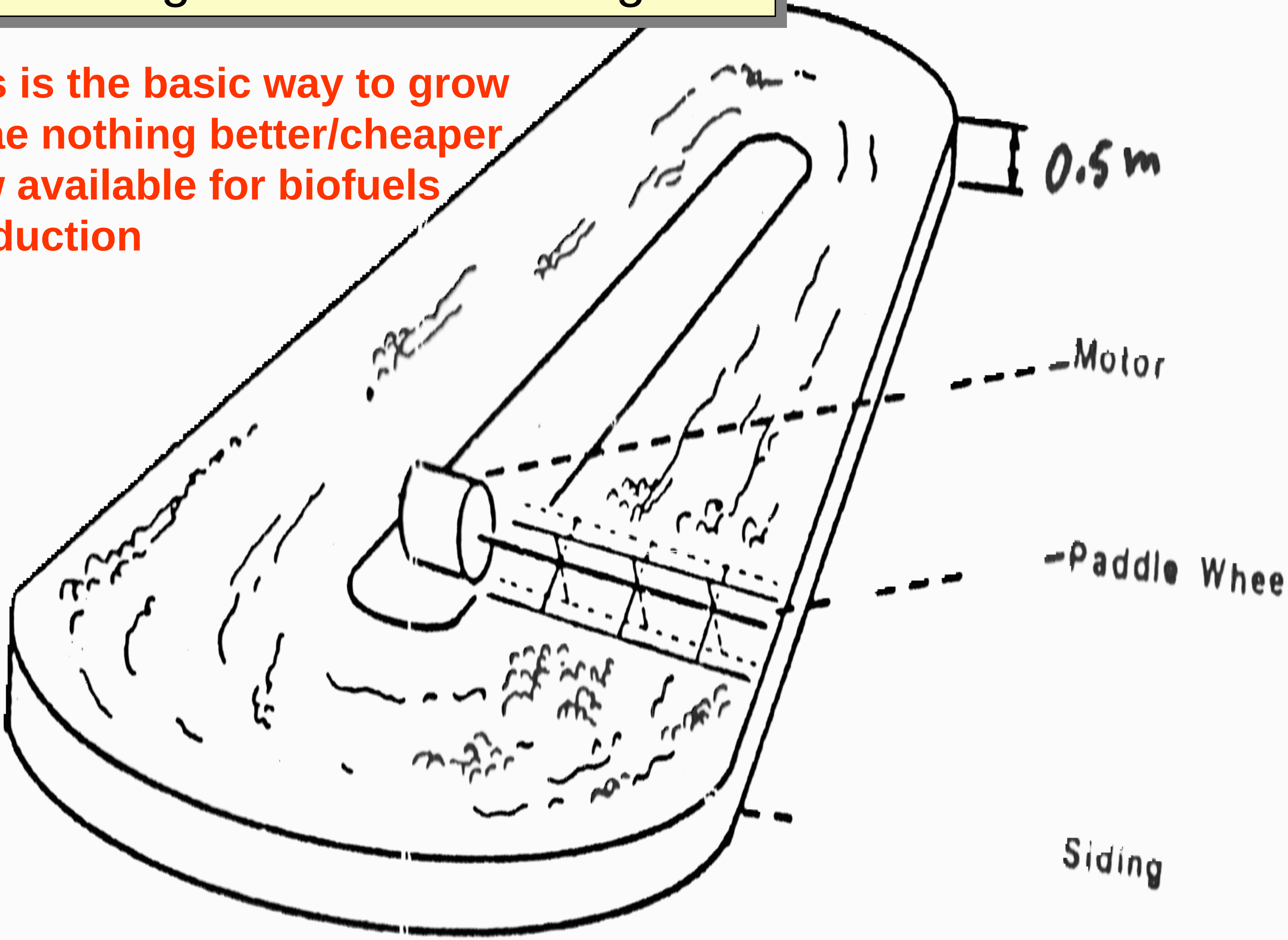
Conclusion: No difference in productivity between them



Tetraselmis suecica

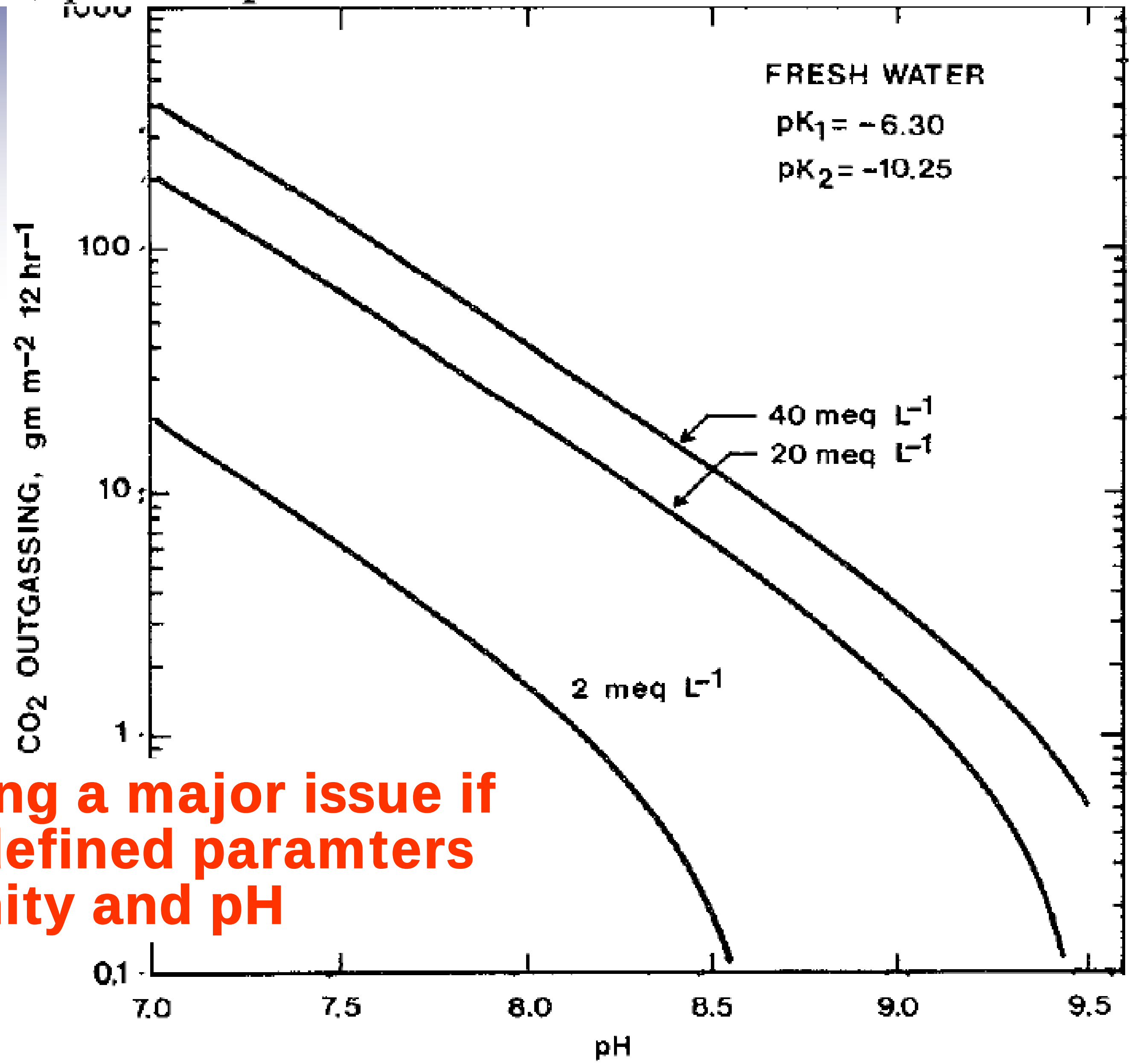
Typical High Rate Pond Design

This is the basic way to grow algae nothing better/cheaper now available for biofuels production



MICROALGAE PILOT PONDS IN ROSSWEL, NEW MEXICO for Microalgae Production (J. Weissman, P.I., Microbial Products, Inc., 1989-1990 – DOE NREL ASP Project)

Figure 5. CO_2 outgassing as a function of constant pH and alkalinity. For both cases, pond depth = 0.2 m and K_L = 0.1 m/h.

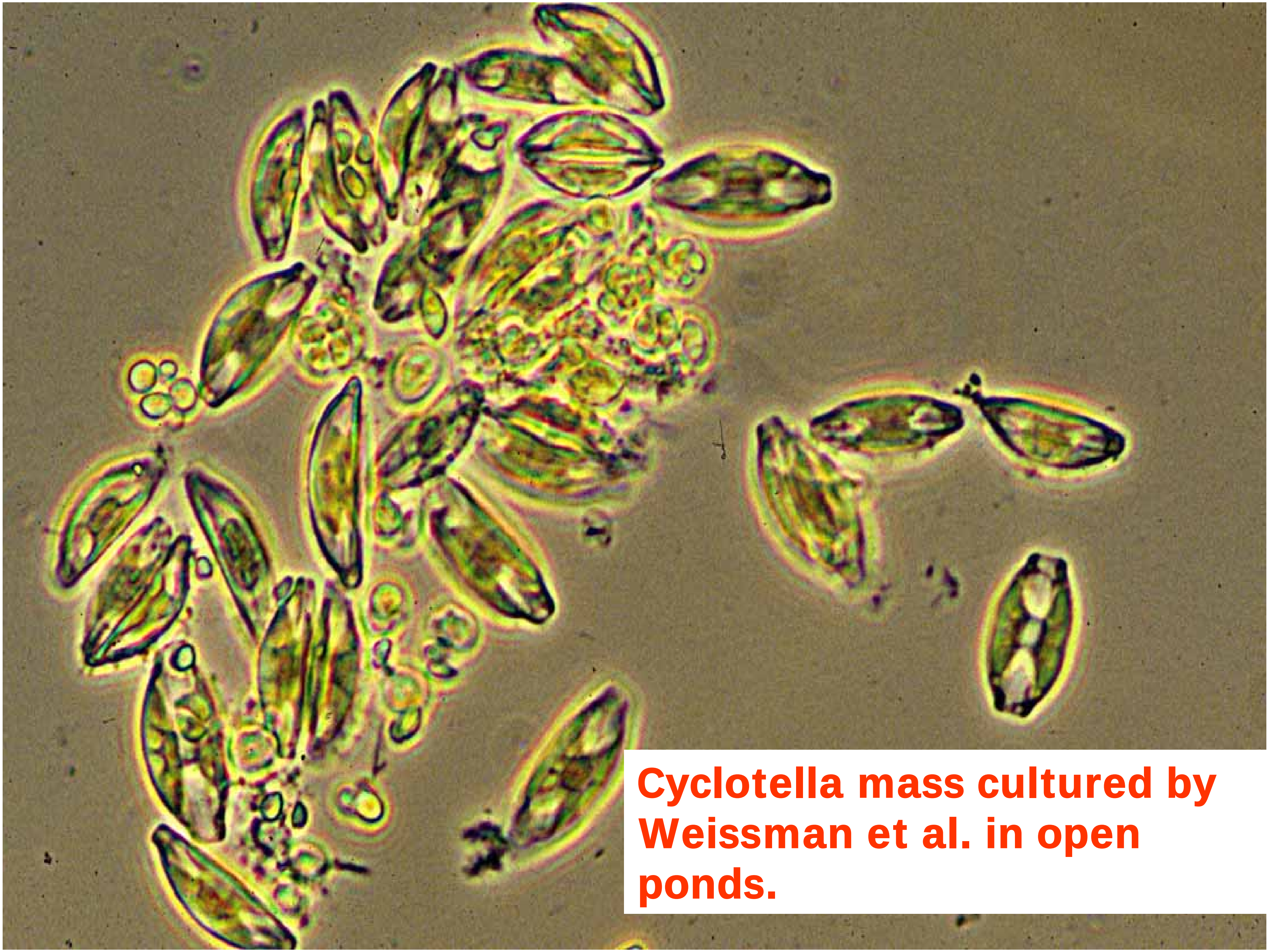


Outgassing a major issue if outside defined paramters of alkalinity and pH

CO_2 Mass Transfer Coefficients in Roswell Ponds (from Weissman et al., 1990)

Depth cm	Velocity cm/sec	k_L cm/sec	Surface Renewal, sec
10	10	3.9×10^{-4}	150
10	30	1.4×10^{-3}	12
30	10	2.2×10^{-4}	480
30	30	0.8×10^{-3}	37

Efficient CO_2 use at <30 cm depth, <30 cm/sec velocity



Cyclotella mass cultured by Weissman et al. in open ponds.

ROTIFERS (ALGAE GRAZER] – another challenge

ASP Production of Microalgae for Fuels

Conception of microalgae biodiesel production Aquatic Species Program, U.S. DOE NREL 1987. Note raceway growth and settling-harvesting ponds

Techno-economic analyses of microalgae biofuels

Benemann, J.R., P. Persoff, W.J. Oswald, 1978 **Cost Analysis of Algae Biomass Systems** ("100 Square Mile System") U.S. DOE

Benemann, J.R., R.P. Goebel, R.P., J.C. Weissman, and D. C. Augenstein 1982. Microalgae as a source of liquid fuels. Final technical Report to U.S.DOE BER

Weissman, J.C., and R.P. Goebel, 1987. Design and analysis of microalgal open pond systems for the purpose of producing fuels: A subcontract report US DOE- SERI

Benemann, J.R. and W.J., Oswald 1996, Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass. Final eport. US DOE-NETL

NOTE: these reports do not conclude that we can produce algae oil, they define long-term research needed to develop such processes

Perspective of microalgae production now

ALGAL LIPID (OIL) CONTENT SOME OLD DATA

NS=N Sufficient, ND=N Deficient; [#] No. days of batch growth

SPECIES	LIPID CONTENT NS	ND
Chlorella pyrenoidosa	20(80)	35(17)
" "	18(?)	65(?)
" "	25(?)	40(?)
" "	20(?)	70(?)
" "	25(?)	35(4)
" sp. strain A	20(log)	45-53(17-26)
" strain 10-11	19(log)	18-26(5)
Bracteacoccus minor	25(?)	33(?)
Chlorella vulgaris	27-33(?)	54(?)
Nitzchia palea	22(log)	39(7-9)
Chlorella pyrenoidosa	14(log)	36(7-9)
Oocystis polymorpha	13(log)	35(11)
Monollanthus salina	41(log)	72(11)
Nannochloris sp.	20(log)	48(11)
Scenedesmus obliquus	26(log)	47(22)
Chlorella vulgaris	24(log)	64.5(28)

However: high oil content does NOT mean high oil productivity!

THE ALLURE OF MICROALGAE BIODIESEL

Oil yields	liters/ha-yr	barrels/ha-yr
Soybeans	400	2.5
Sunflower	800	5
Canola	1,600	10
Jathropha	2,000	12
Palm Oil	6,000	36
Microalgae	60,000-240,000*	360 -1500*

*****Projected high yield (by GreenFuel Technologies) is ~2 x theoretical efficiency (~22,000 gal/acre-yr).

Low is maximum yield projected for long-term R&D

Near-term (5 yrs?) productivity is perhaps half this!

Microalgae Biodiesel – Reality Check .

GreenFuel Technologies 2007

U.S. DOE- NREL Aquatic Species Program ~1987

Their own algae/lab

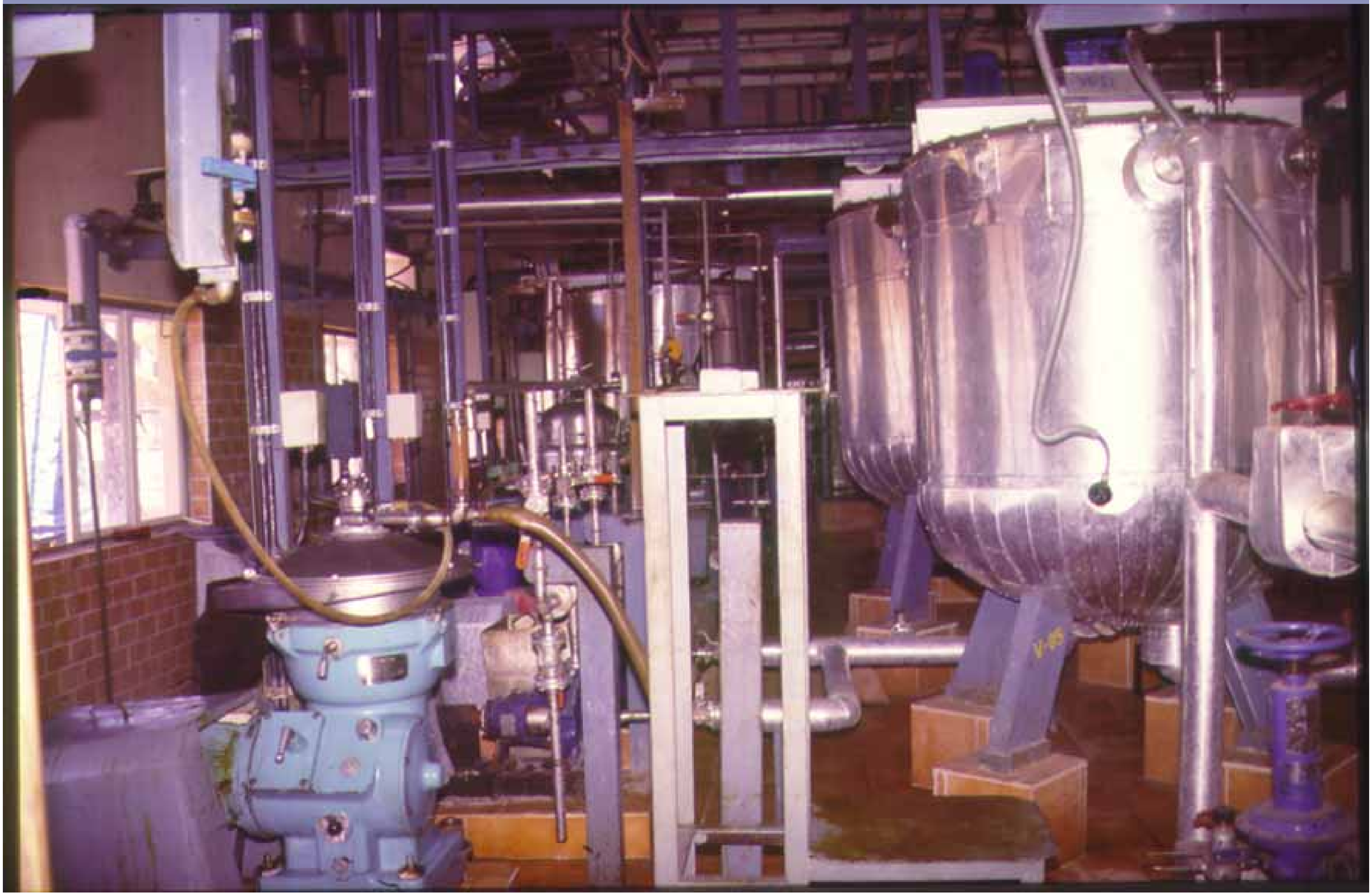
Seambiotics/ Inventure

Dec 2005: 1st Car in world to run Algae Biodiesel
~10/90 algae biodiesel/soy biodiesel >1500 km

<u>1st car in world fueled with algae biodiesel</u>

Dunaliella salina b-carotene production ponds, India, source of the algae oil used

D. salina oil extraction systems



1st Production of Microalgae Biodiesel - Dec 2005

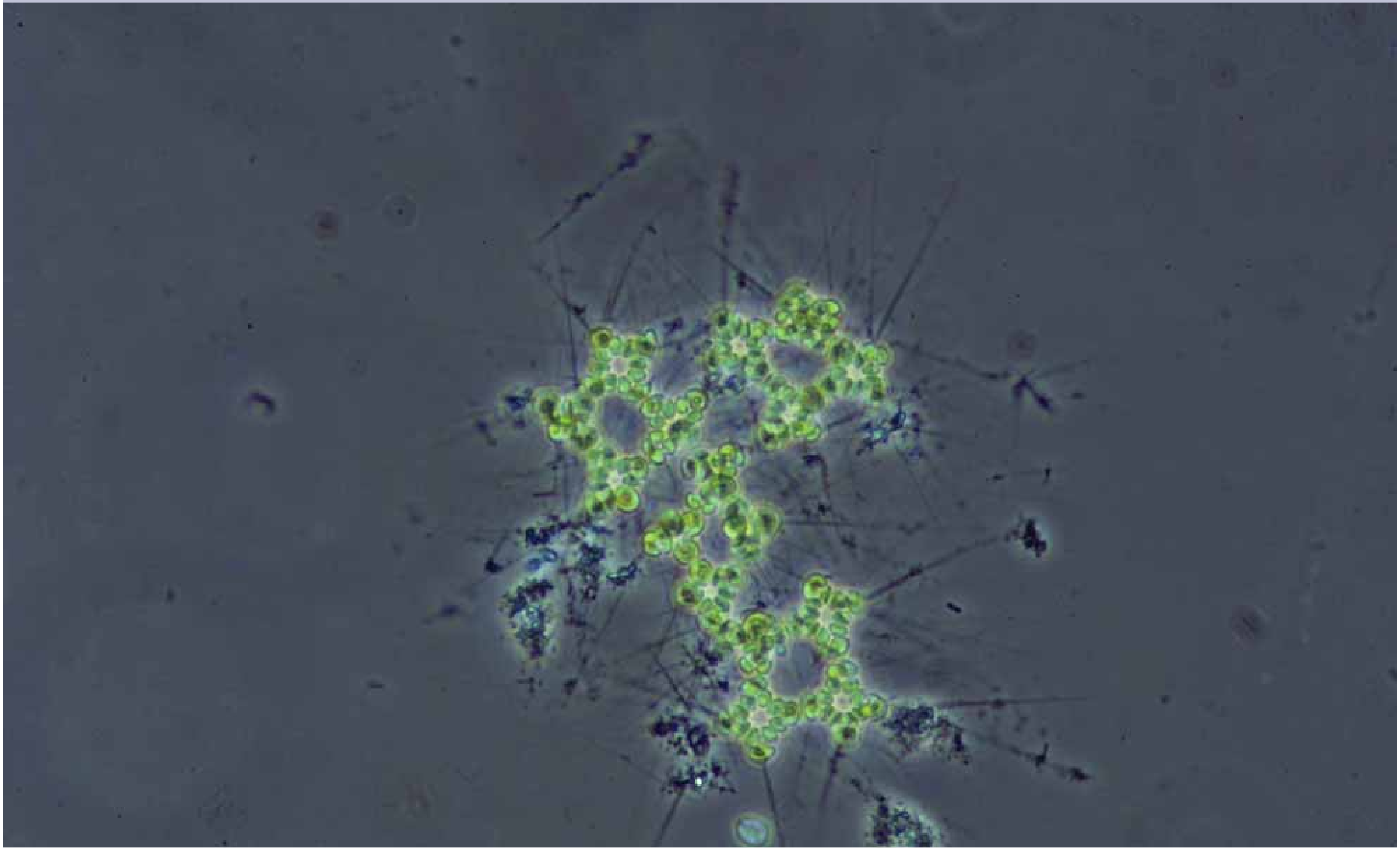
Ramin Yazdani (Davis, CA) with sample of the ~1 barrel B10 algae biodiesel he made in his backyard refinery from a *Dunaliella salina* extract John Benemann supplied

Near-term Algae Biodiesel: as co-product from Wastewater treatment (Napa, CA, Ponds ~ 300 ac)

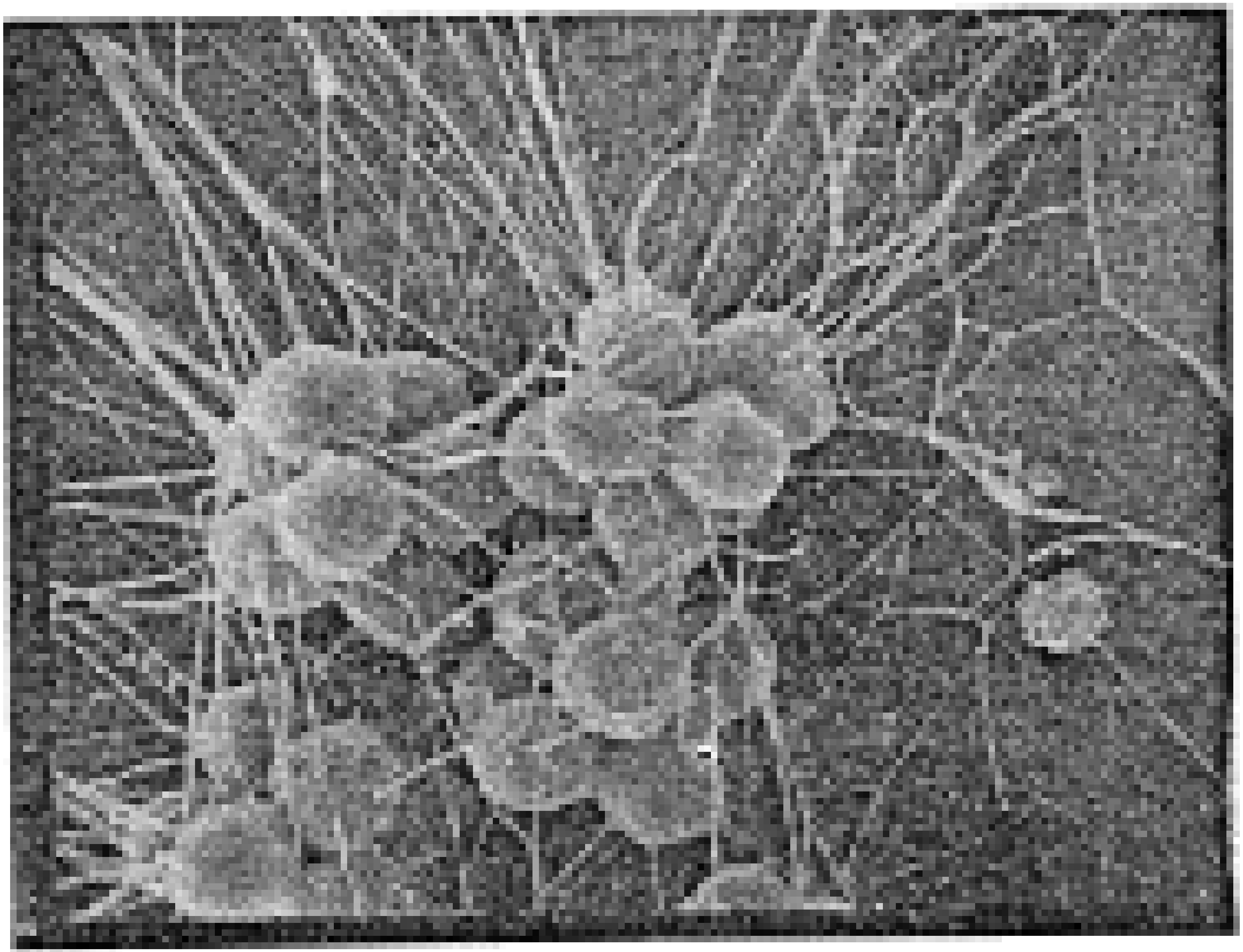

St Helena, California Wastewater Treatment Ponds
High Rate→ Ponds

BIOFLOCCULATION OF MICROACTINIUM

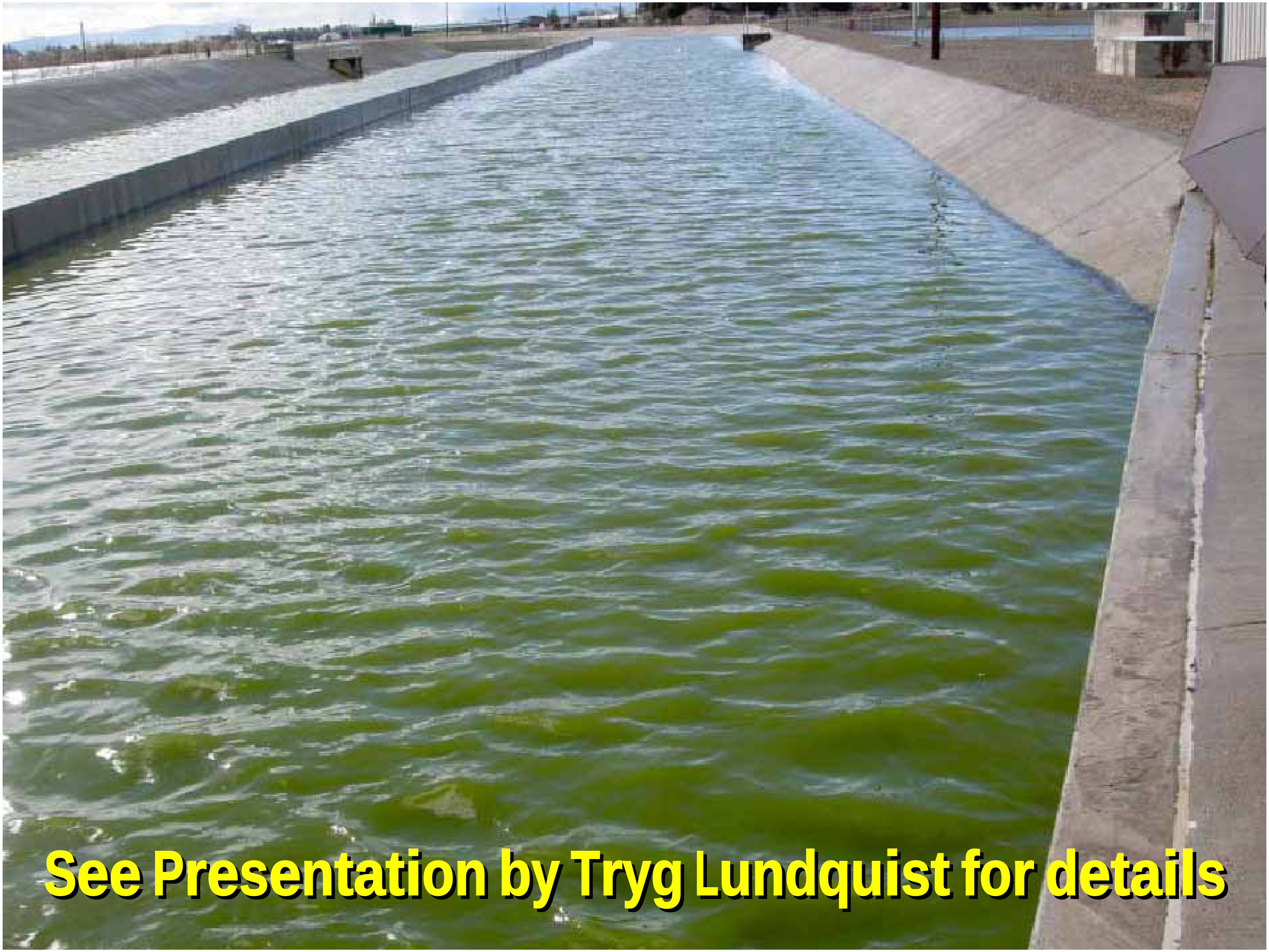
these spontaneously forming flocs settle rapidly for low-cost harvesting a key issue in mass culture of microalgae



Mechanism of Bioflocculation of *Micractinium*



Paddle Wheels at existing WWT Ponds, a site for planned technology demonstration project


See Presentation by Tryg Lundquist for details

R & D TARGETS

- **Isolate/select algal strains for mass cultures**
- Manage ponds for algal species and culture stability
- Maximize overall algal biomass productivity
- Maximize C-storage products and co-products
- Demonstrate large-scale, low cost algal cultivation
- Develop low cost harvesting technologies
- Processing for biofuels and higher value co-products.
- Demonstrate waste treatment - nutrient recovery

Mutants of Cyclotella with reduced Antenna Size

Polle, Weissman, et al.

SOME CONCLUSIONS

1. The problem is not making oil from algae, it is making algae with oil, actually it's just making algae
2. Need to improve current best commercial practice and technology by over a factor of ten
3. There are many problems, and many, many claims to solutions. No universal, only specific, solutions
4. Example: harvesting is species specific, not generic
5. We MUST develop high productivity strains
6. Photobioreactors limited to inoculum production
7. Wastewater treatment is the near-term application

Microalgae Biofixation Network - Members

CGTEE and Eletrobrás (Brazil)

ONGC and TERI (India)

NIWA, NZ

SRI International (USA)

PNNL (Pacific Northwest National Laboratory)

FINAL THOUGHTS

- "The successful growth of algae is more or less an art and a daily tightrope act with the aim of keeping the necessary prerequisites and various unpredictable events involved in algal mass cultivation in a sort of balance" (Wolfgang Becker, posted at commercial production plant)

- "The **advantage** of biofuels and other renewable energy sources is that they will be so scarce and expensive that we will need to use them very frugally instead of wasting them wantonly as we do now with fossil fuels, and would with nuclear energy" (John Benemann).