Some Thoughts About Stromatolites, (Microbialites)

Energy Conservation and Lake Biogeochemistry

Presentation at Laguna Bacalar Symposium

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Ken Nealson
Wrigley Professor of Environmental Sciences
University of Southern California
knealson@usc.edu

Mi nombre es Ken Nealson
Soy un profesor de Ciencias Ambientales en
la University of Southern California en Los Angeles, California

Durante 12 años he trabajado con “River” Kaster en Wisconsin
Y tuvo el honor de ser invitados a participar en este simposio

Hoy quisiera compartir algunas reflexiones acerca de mi amor -
-
Las bacterias que se forman y se disuelven minerales

También me gustaría hablar brevemente acerca de algunas nuevas tecnologías para la eliminación de desechos - la tecnología que podría ser muy útil para la Laguna de Bacalar

Begin with Movie – Microbial Respiration of Metals

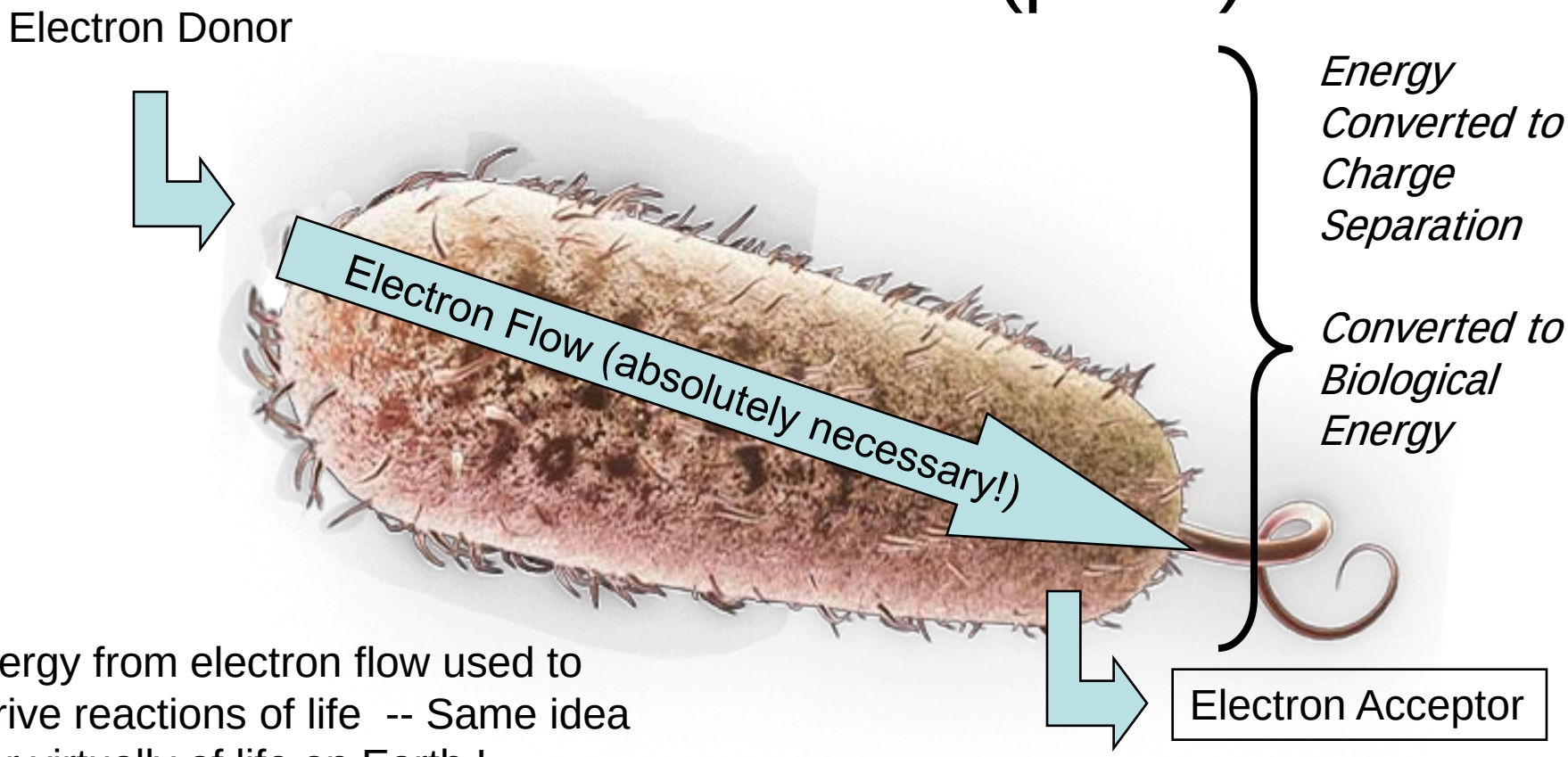
Bacteria that in the absence of oxygen

are able to utilize solid metal oxides as

an oxygen substitute !!

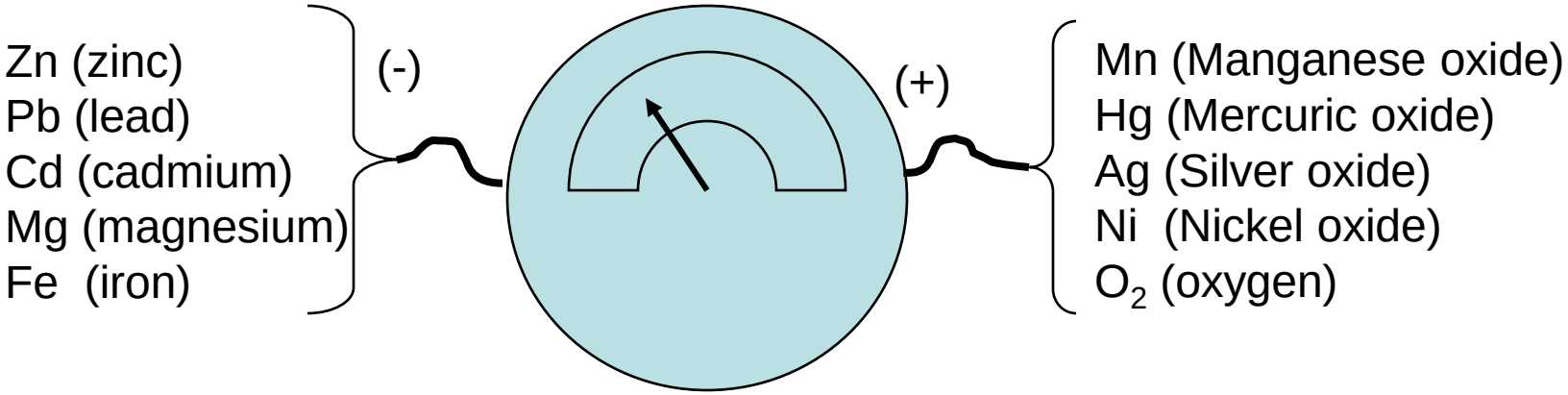
We call it breathing rocks!!

How Life Works** (part I)

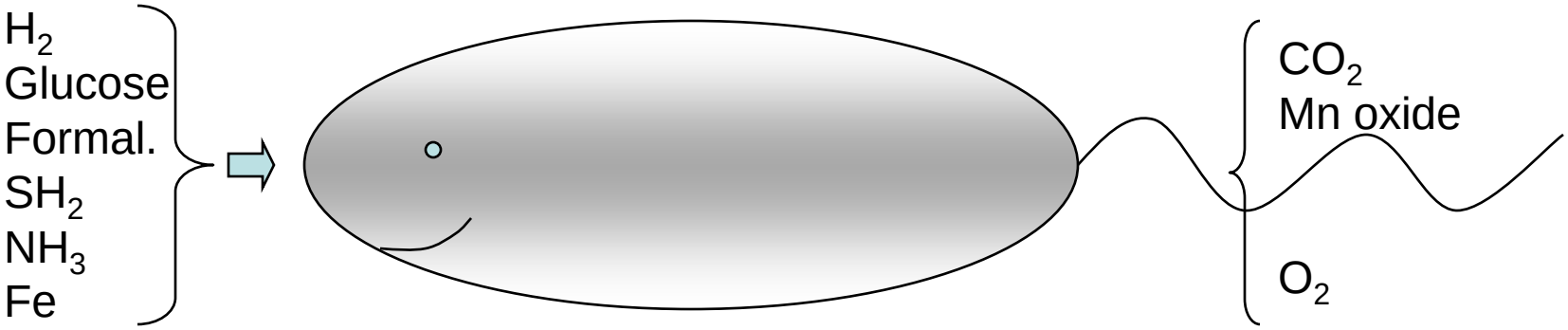


Energy from electron flow used to drive reactions of life -- Same idea for virtually of life on Earth !

ELECTRONS MUST FLOW!!



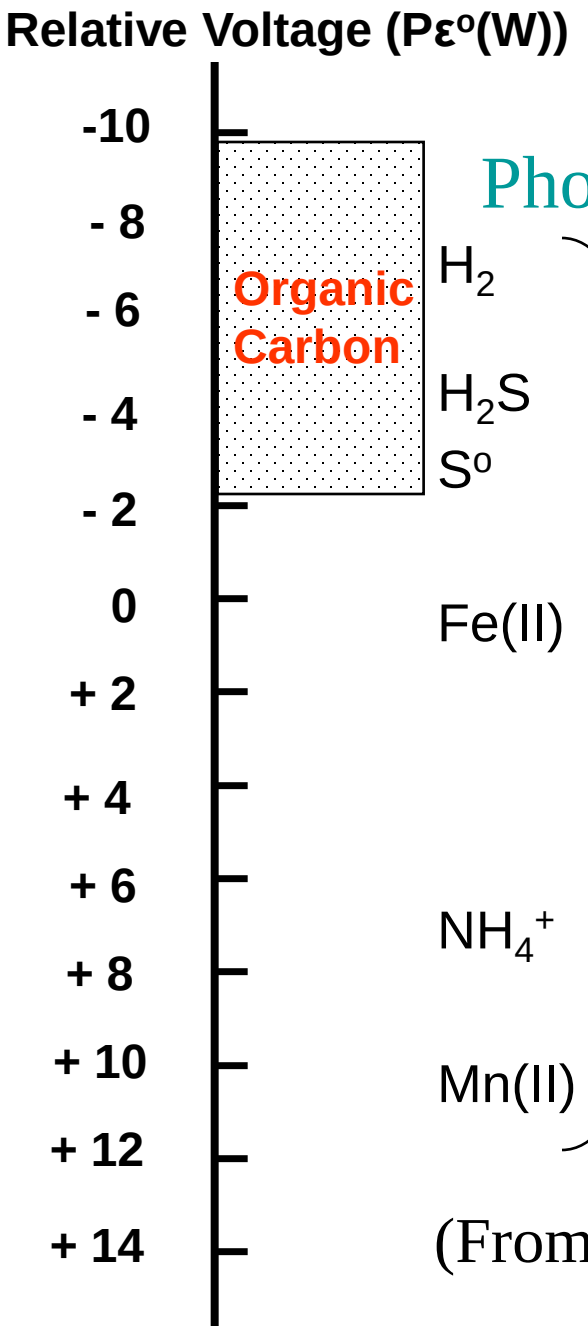
MANMADE BATTERIES !!



MICRO-BIOLOGICAL BATTERIES !!

In both cases, current must flow for energy to be utilized!

Fuels of Life: Sunlight, Organics & Inorganics



Photoreductants from **sunlight** via PS

Chemical Reductants -- from hydrothermal reactions or via anaerobic respiration

These inorganic fuels used only by prokaryotes (bacteria & archaea)

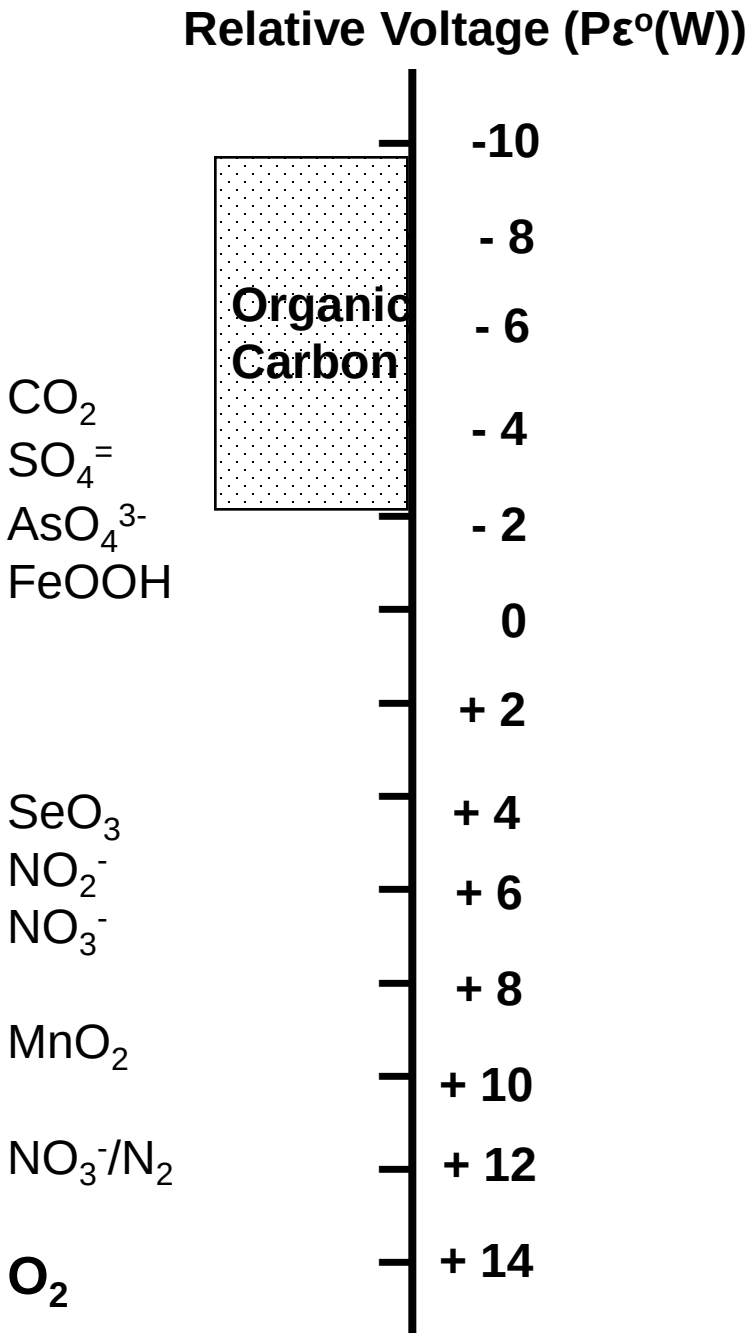
(From Stumm & Morgan, Aquatic Chemistry)

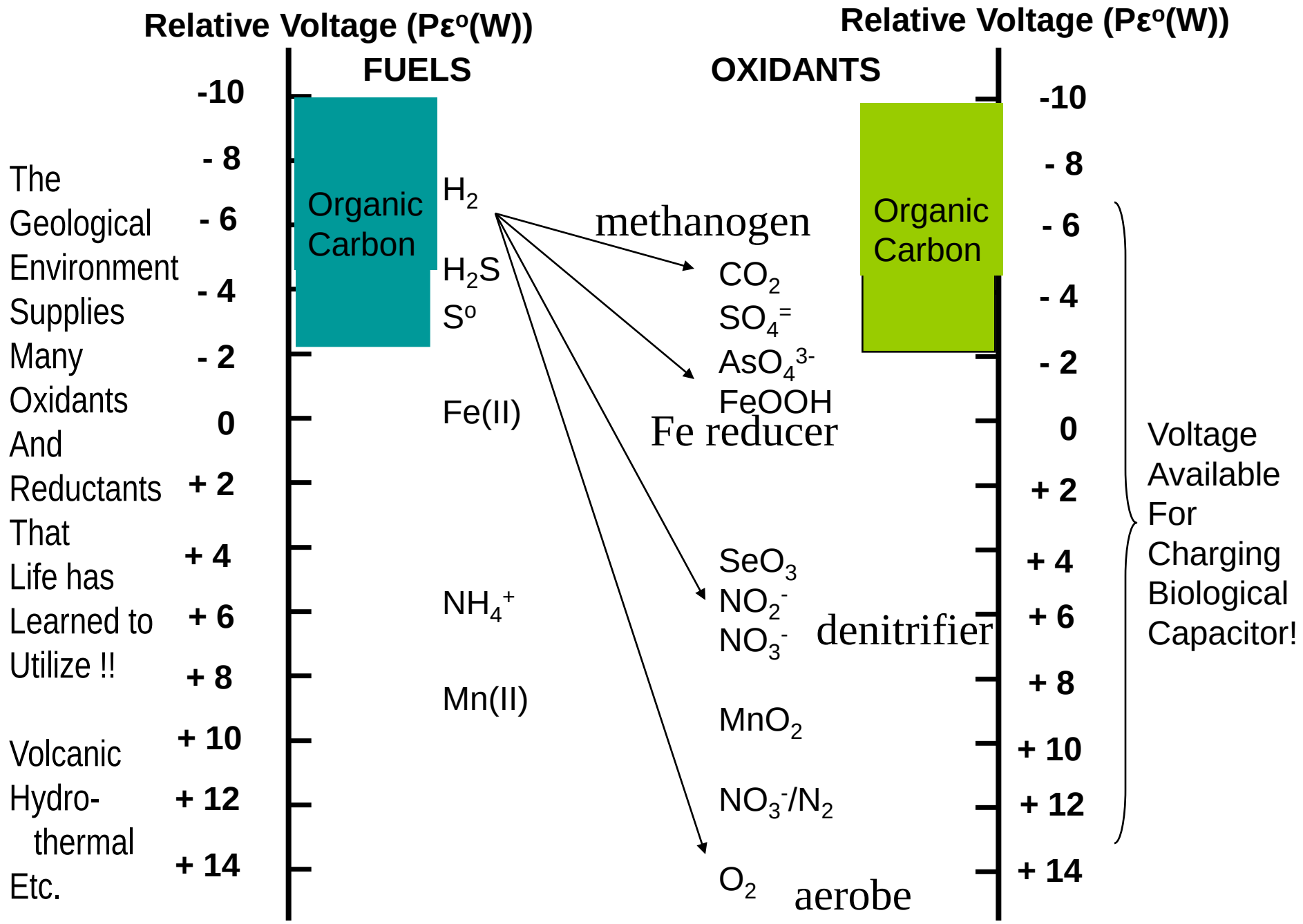
Oxidants of Life:

Oxygen is best oxidant
(most energy)

Used by all eukaryotes

Inorganic compounds are
used only by prokaryotes
(Bacteria and Archaea)




Relative Voltage (Pε°(W))
FUELS
OXIDANTS
Relative Voltage (Pε°(W))
-10
- 8
- 6
- 4
- 2
0
+ 2
+ 4
+ 6
+ 8
+ 10
+ 12
+ 14
The Geological Environment Supplies Many Oxidants And Reductants That Life has Learned to Utilize !!
Volcanic Hydro-thermal Etc.
Organic Carbon
H2
H2S
So
Fe(II)
NH4+
Mn(II)
methanogen
CO2
SO4=
AsO43-
FeOOH
Fe reducer
SeO3
NO2-
NO3-
denitrifier
MnO2
NO3-/N2
O2
aerobe
Organic Carbon
Voltage Available For Charging Biological Capacitor!

Bacteria that emit light: Chemical energy to Biological energy to Light energy !!

Bacteria take energy of almost any kind
Turn it into biological energy
Then use it for what they want !

Light Motility Growth
Electricity !!!

1. Bacteria are masters of using many different energy sources
   (They eat anything!)
   If a rock is made of minerals that will give up electrons, microbes
   know how to “eat the rock”

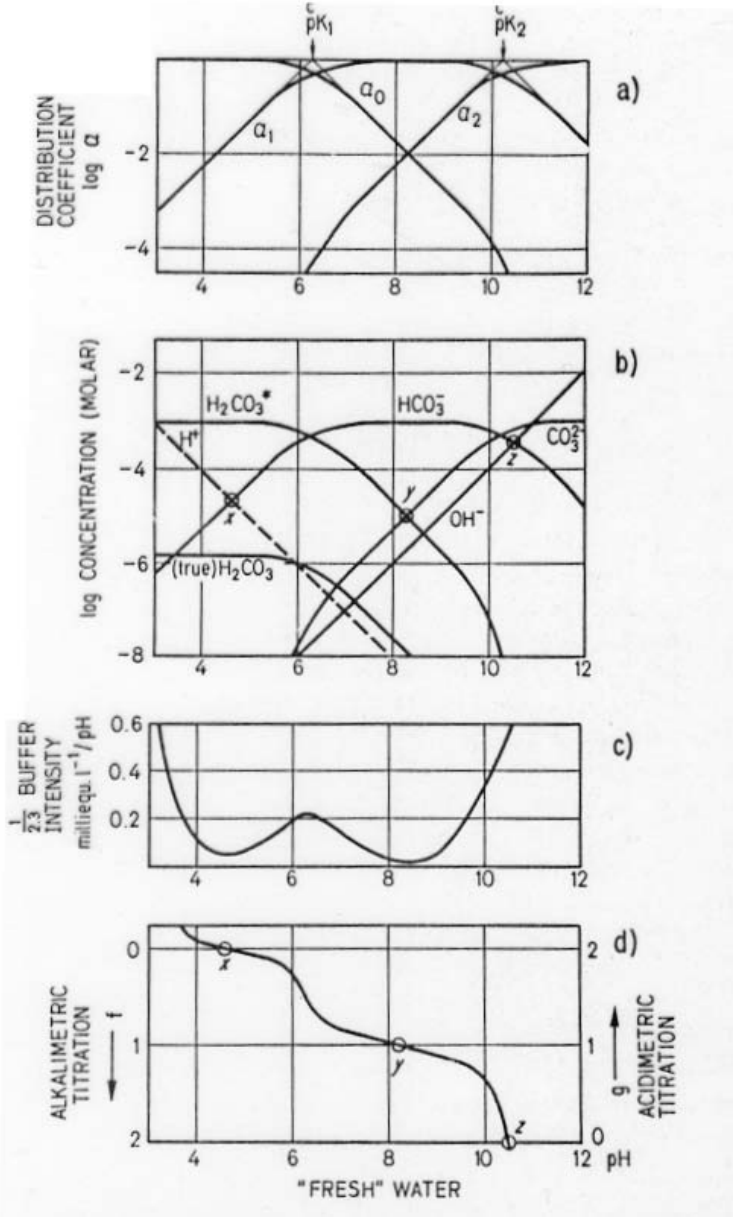
2. Bacteria are masters at using many different oxidants for respiration
   (they breathe anything!)
   If a rock is made of minerals that will accept electrons, microbes
   know how to “breath the rock”

3. Bacteria create many by-products when they grow, but mostly produce
   more bacteria.
   They Change the environment via by-products

One of the things they do very well is change the pH

1. Excretion of acids
2. Excretion of ammonia (pH goes up)
3. Heterotrophic bacteria produce CO_2 (pH goes down)
4. Photosynthetic bacteria take up CO_2 (pH goes up)

Carbonate buffered systems:



Freshwater carbonates:

Decrease CO_2
pH increases

pH increase causes rock formation

Thus: Turn on lights, get carbonates

Expect carbonates to be formed in the light, during the day

Shape is probably function of shape of rock, and the wave action.

Bacteria are masters at forming biofilms

Biofilms – layers of microbes on surfaces

Surface can be inert – glass
Surface can be food (electron donor)
Surface can be oxidant (electron acceptor)

Most activity of microbes goes on in biofilms

In thinking of microbialites (stromatolites), must always think about biofilms

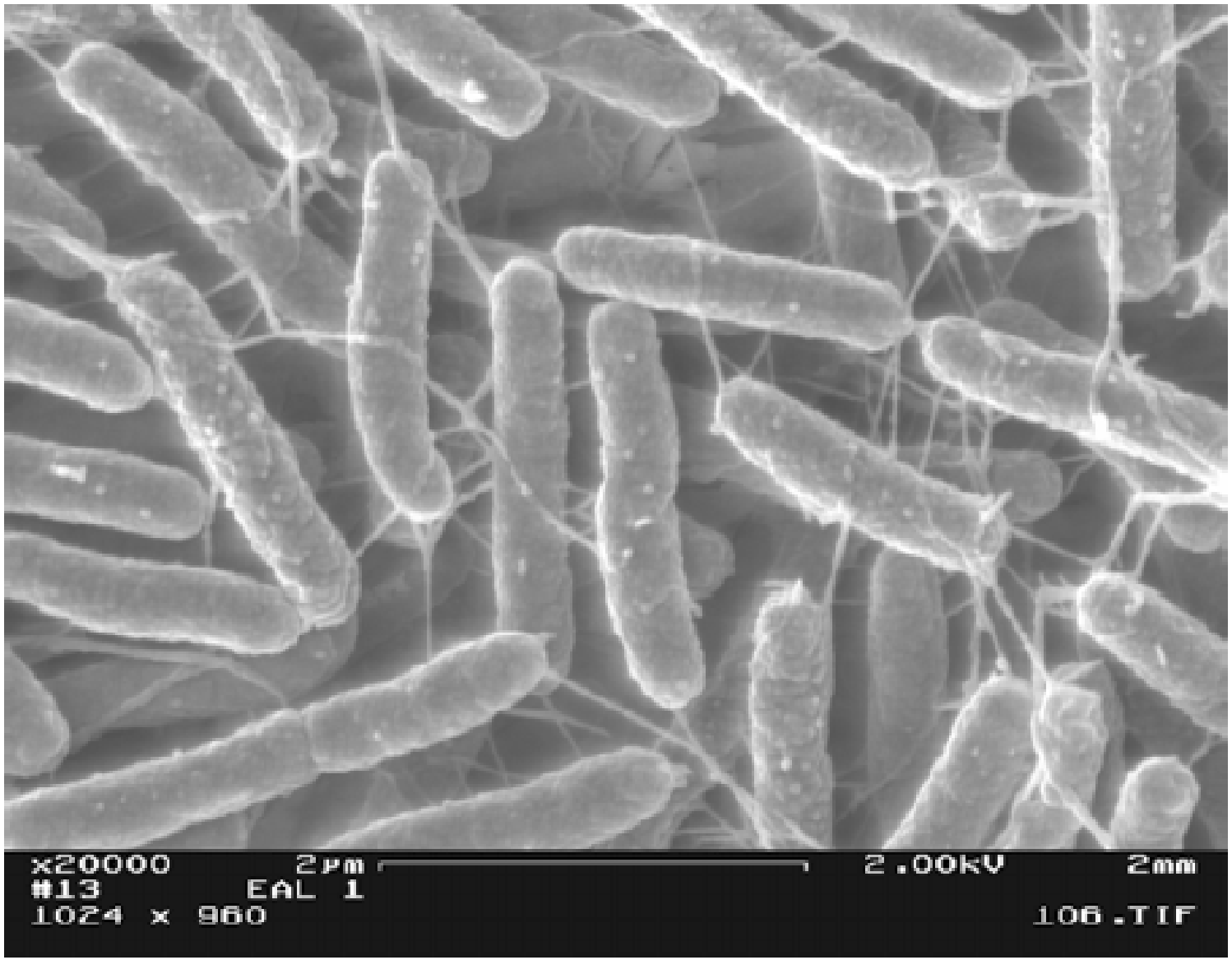
Leads to structures similar to ones noted yesterday by Bob Ginzberg

Hypothesis for Bacalar Microbialites:

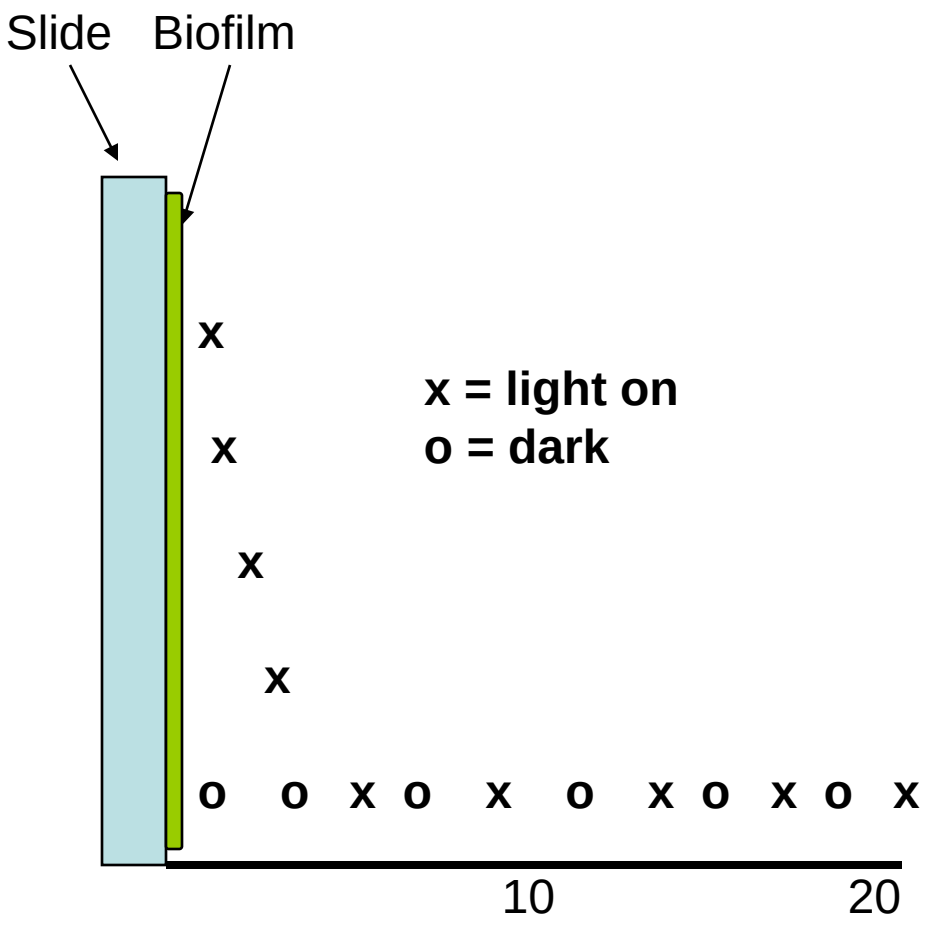
1. Biofilm of photosynthetic bacteria (cyanobacteria likely)
2. Photosynthesis results in CO_2 removal
3. pH goes up
4. carbonate rock precipitates
5. cyanobacteria glide to the surface

This is consistent with what we see, not necessarily correct!!

Biofilm of *Shewanella oneidensis* cells: on mineral surface



Light-induced pH changes



Richardson, L., C.Aguilar and K. Nealson. 1988. Manganese oxidation in pH and 02 microenvironments produced by phytoplankton. Limnol. Oceanogr. 33:352-366.

Bacalar Stromatolites:

Growing now !! Proper studies can determine rates and mechanisms of growth

Clue to the past

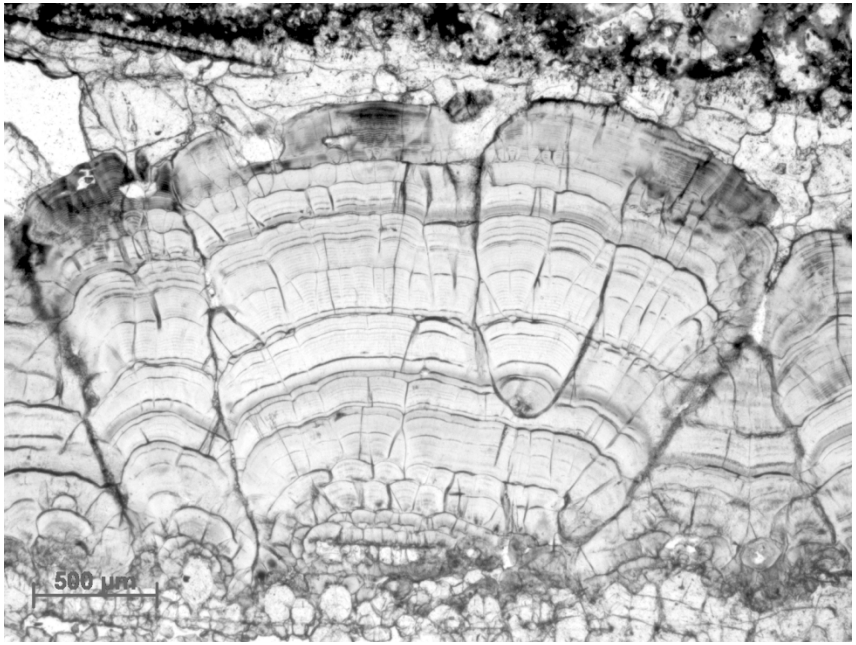
Mistake is to think that there is only one way to form stromatolites and that only one explanation is needed.

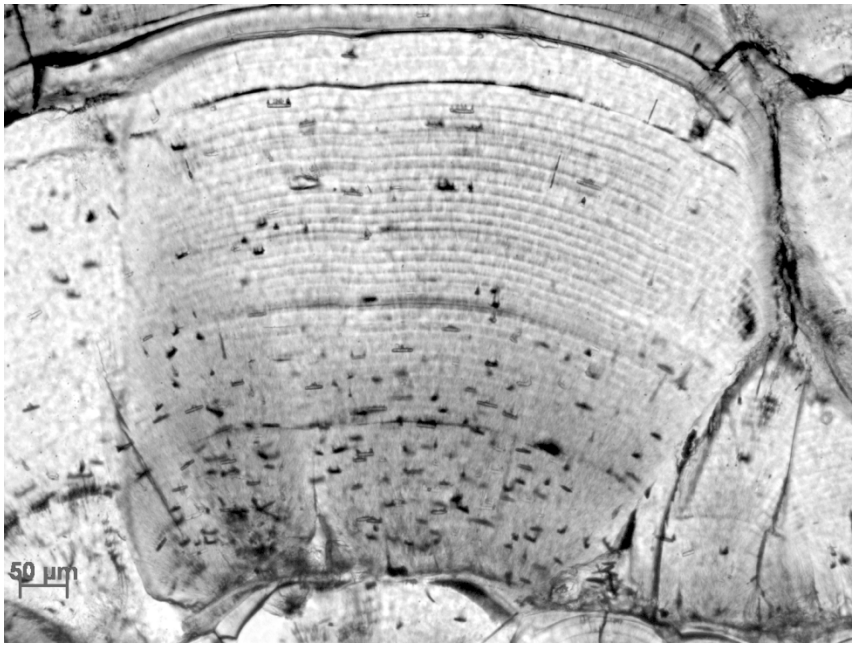
There are only a few stromatolites known these days that are growing. Very important area with regard to Earth history.

Movie of Layered Structure Formation

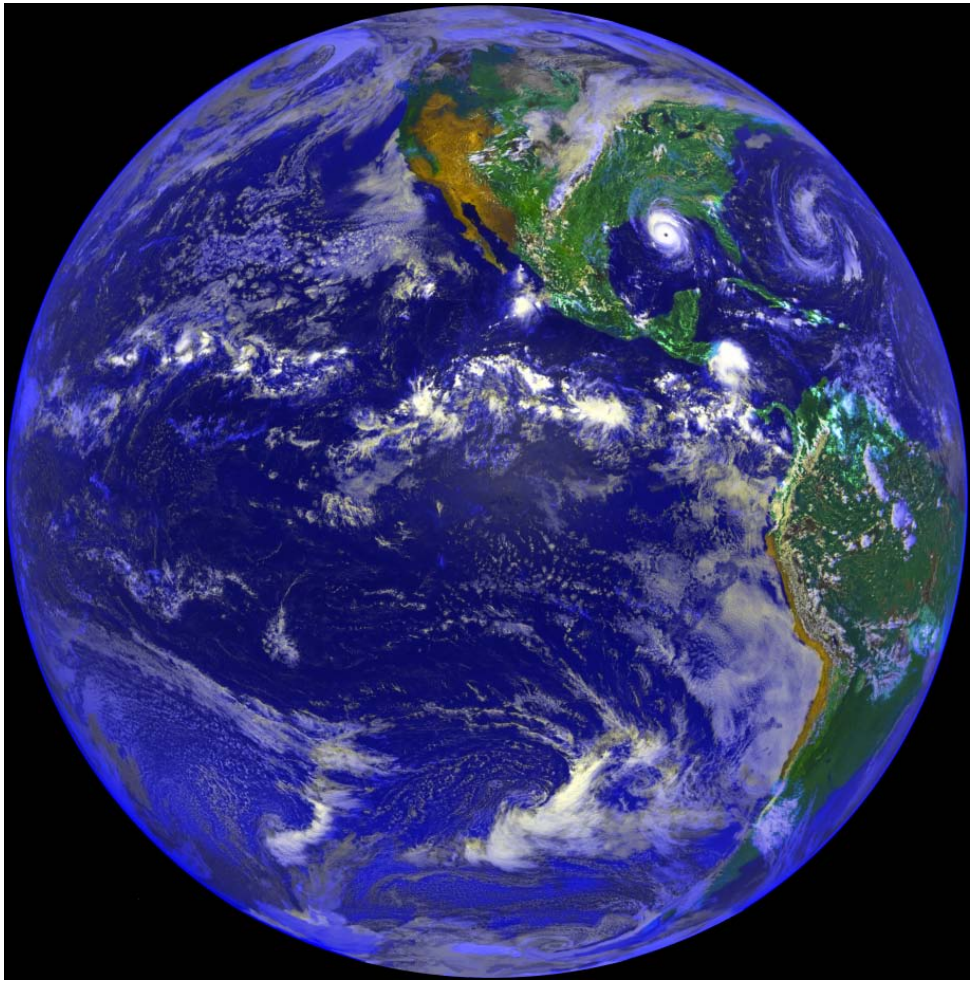
The Cedars:
A high pH Environment
in Northern California, USA

Layered Structures formed in the Cedars Environment
Totally Chemical Process !! Many ways to form layers !!



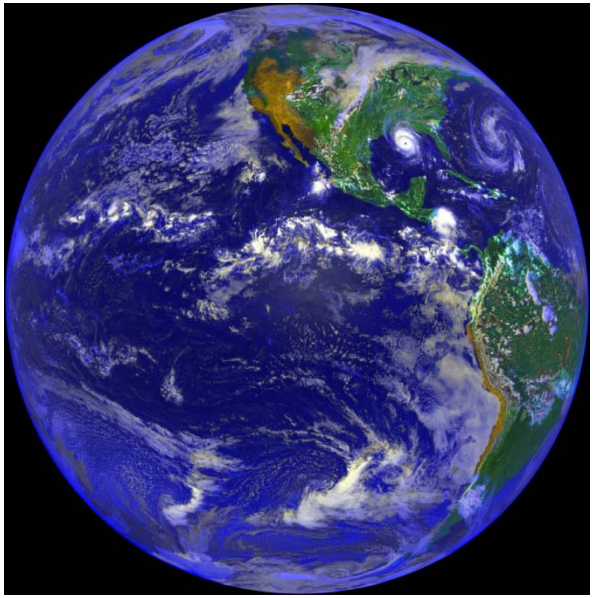


Microbial fuel cells (MFCs) for sludge treatment and water production



The Need

- Domestic
  - EPA estimates $134 billion required to accommodate wastewater treatment needs by 2024.
  - EPA estimates a water infrastructure funding need in California to be $20 billion over the next 20 years.
- Global
  - Growing economies and overpopulation creating dangerous and unquantified damage to water supplies.
  - 2 million children die every year from diarrheal diseases (including cholera) contracted from unsafe water supplies.

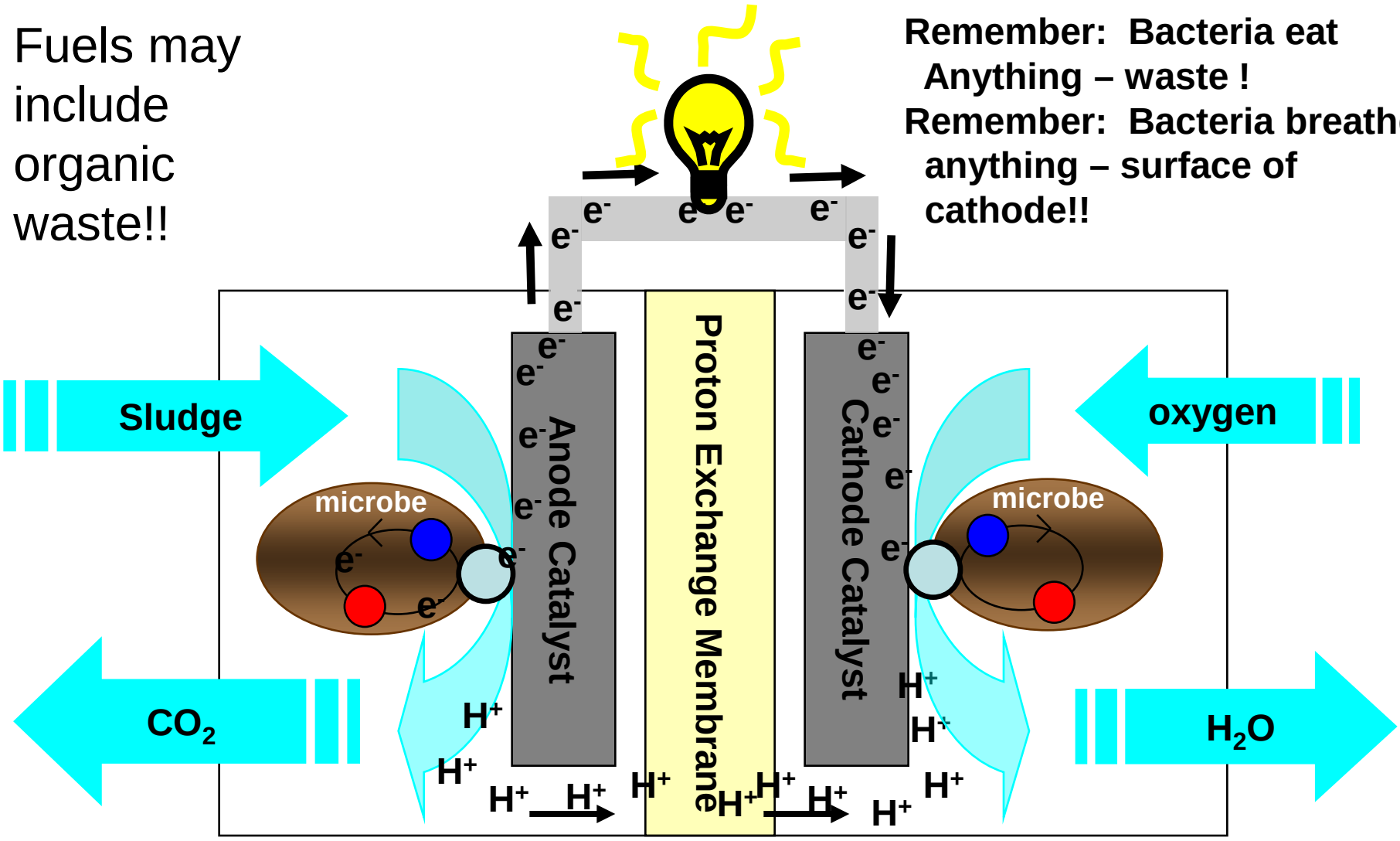


New technologies for wastewater treatment are required to cost effectively meet future demands and counter existing health issues

Microbial Fuel Cells – A promising technology

Fuels may include organic waste!!

Remember: Bacteria eat Anything – waste !
Remember: Bacteria breathe anything – surface of cathode!!



= Outer membrane electron carriers (cytochromes)

= Ion Exchange Membrane

= Oxidized carrier molecule

= Reduced carrier molecule

Microbial Fuel Cell Reactions:

Anode: anaerobic

Anode is the electron acceptor !! Nothing else to breathe!

Organic Carbon converted to CO_2 plus electrons plus protons

Electrons travel to cathode on wire (used as electricity)

Protons travel to cathode through solution (membrane)

Cathode: aerobic

electrons plus protons plus oxygen produce pure water !!

Organic waste converted to CO_2 plus pure water

and we get paid for it

- Catalysts are bacteria – inexpensive and versatile
- Capable of converting waste nearly 100%
- No residual sewage sludge
- Reactions are very fast (takes 1/10 time)
- Thus takes much less space
- Reactions are robust (running in the lab for several years now)
- Requires no infrastructure (self powered)
- Very promising technology for the future

Our Targets now:

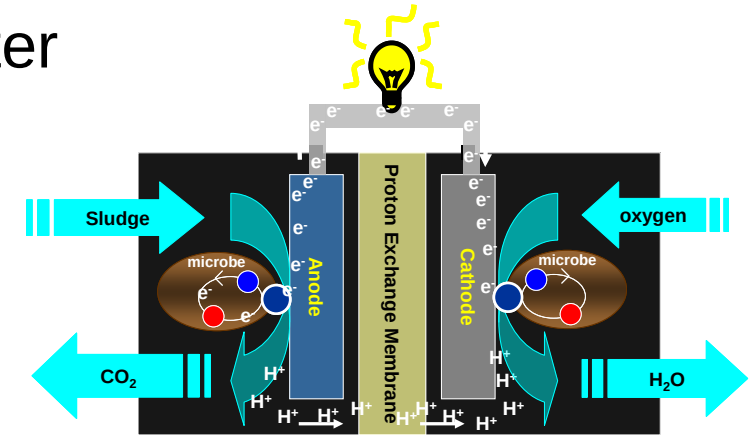
1. Sewage sludge removal via MFC
2. Septic tank units for rapid removal of waste
3. Portable units for households or villages

Sludge = Costly Problem
Costs of treatment in San Diego, CA

- FY08 energy budget for wastewater treatment and disposal: $17 million
- Only 1.5% of energy cost recover through co-generation
- 340 million gallons sludge pumped 17 miles to MBC in one year
- 430 million gallons sludge pumped 5 miles to MBC in one year
- 33,246 metric tons of MBC biosolids transported off-site for disposal
  - 3,274 metric tons to Yuma, AZ (150 miles)
  - 29,982 metric tons to Chula Vista, CA (25 miles)

MFCs for sludge reduction

- MFCs reduce biomass production by moving energy away from microorganisms
- MFCs replace methane production with direct electricity production
- MFCs have been shown to remove between 40-80% BOD from sludge in a twelve hour residence time (Logan, 2004)
- Potential for 37.5 - 75% reduction in transportation costs for biosolids disposal
- MFCs naturally generate fresh water



In MFCs, Sludge = Energy

- Energy content in sludge is estimated as 15 kJ/g or 4.2 kWh/kg (Shizas and Bagley, J. Energy Research, 2004)
- MBC processed ~800 million gallons of sludge in 2007
  - 33,246 metric tons of biosolids
  - Potential for 1.4 x 10^9 kWh
  - $6.7 million at a rate of ($0.05/kWh)

MFC complementary technology to Anaerobic Digestion

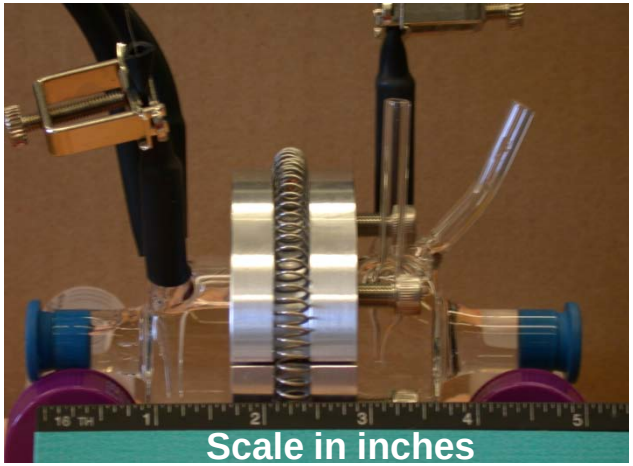
- MFC to reduce total sludge volumes by 30%
- 4 million gallon reactor with retention time of 10 days
  - Capital Cost = $9.8 million (over 20yr) = -$5.34/Kgal
  - O&M (over 20yr) = -$9.75/Kgal
  - Energy recovery (over 20yr) = +24.87/Kgal
    - 10% energy recovery
    - $0.05/kWh
- Net revenue from energy recovery = $9.79/Kgal
  - Does not include savings from decreased costs of production and disposal of biosolids
- “Break-even” cost ($15.10/Kgal) requires 6% energy recovery

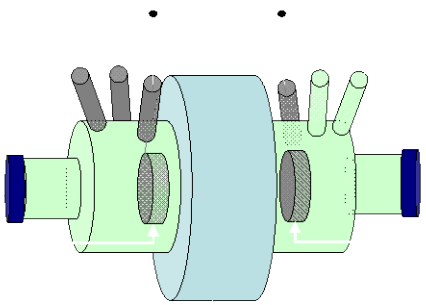
Treatment comparison relative to energy costs

- 30% sludge reduction by MFC = +$24.87/Kgal (by direct electricity)
- Anaerobic digestion = $0.00/Kgal (by methane production and co-generation)
- Desalination via Reverse Osmosis = -$2.73/Kgal (by hydroelectric and other mechanisms)

What we know now

- Demonstrated ability of *Shewanella* to act as a catalyst at the anode and cathode.
- Demonstrated ability of anode enrichment cultures (from wastewater) to generate power and remove organic contaminants.
- Demonstrated ability of many pure cultures to produce power.
- The genes associated with power production in the organism *Shewanella oneidensis* MR1.





MFC Feeding Wastewater

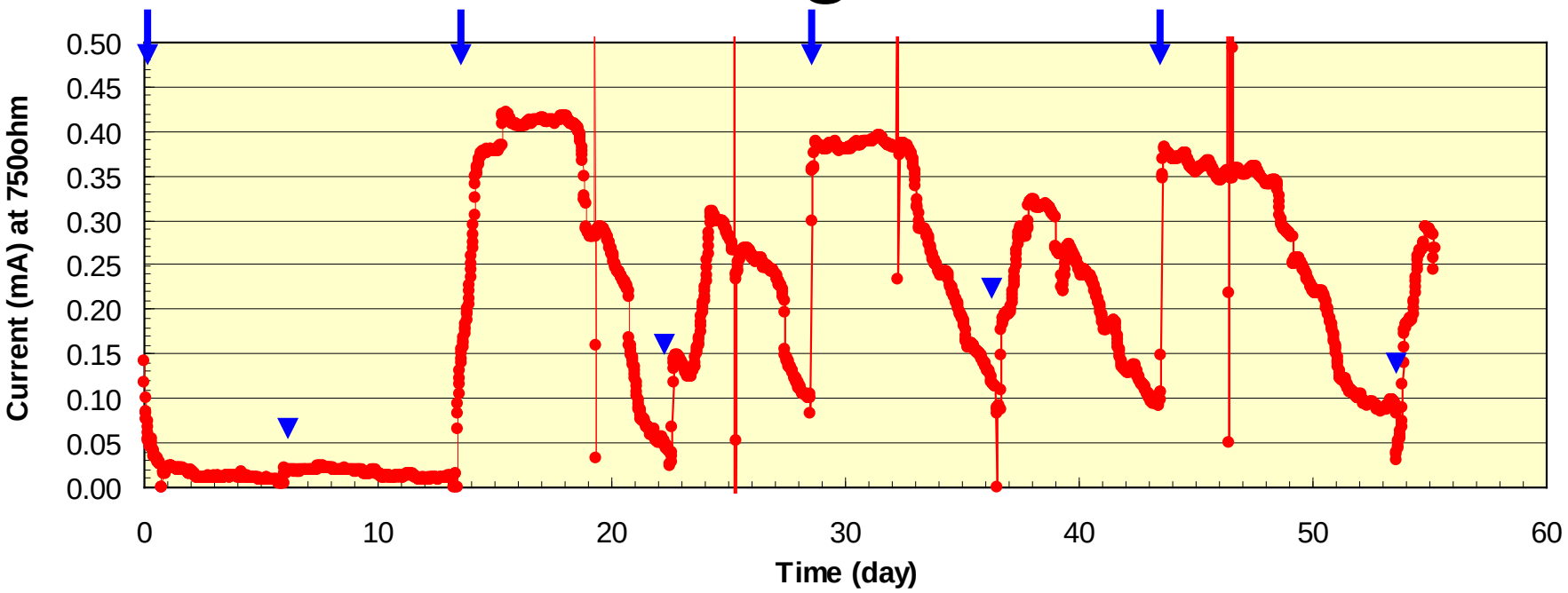
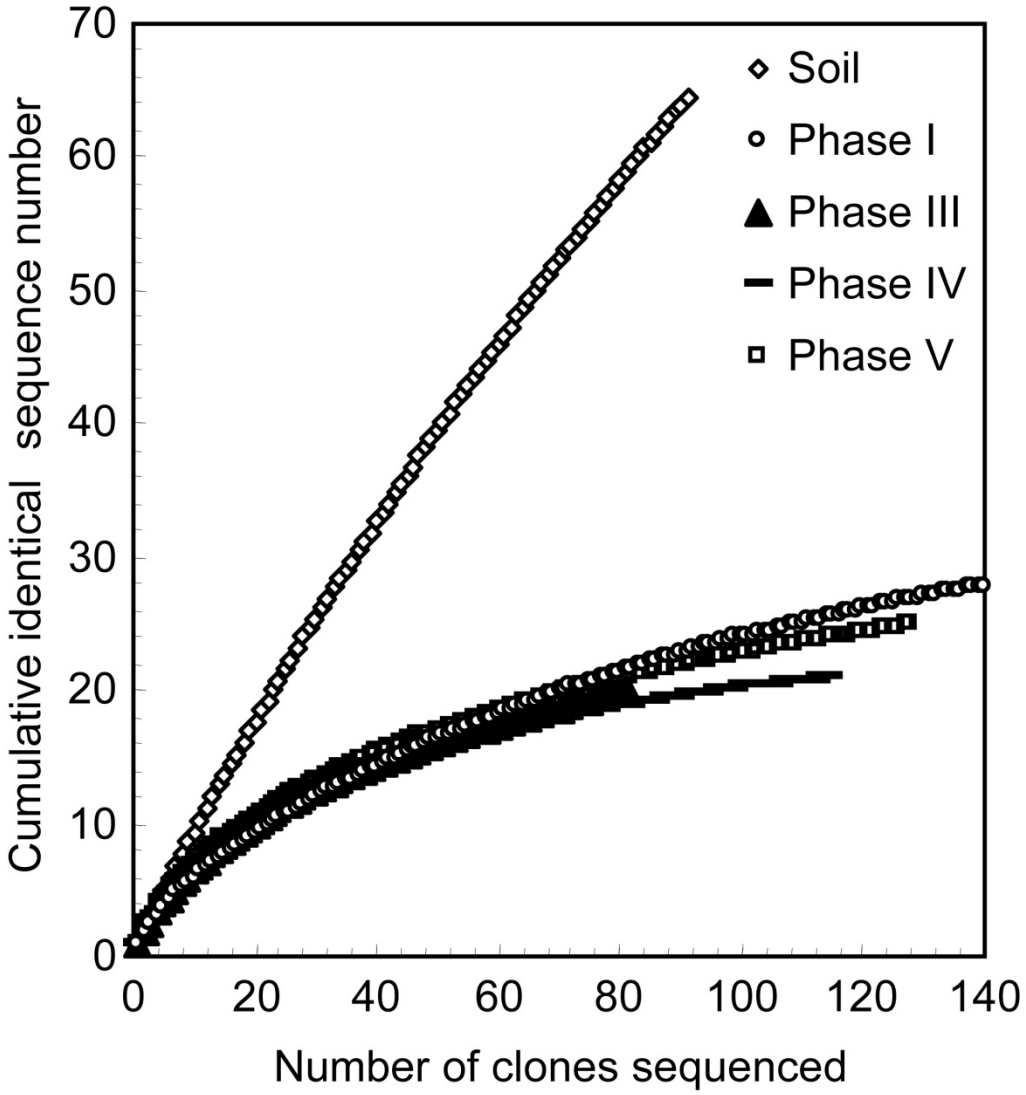


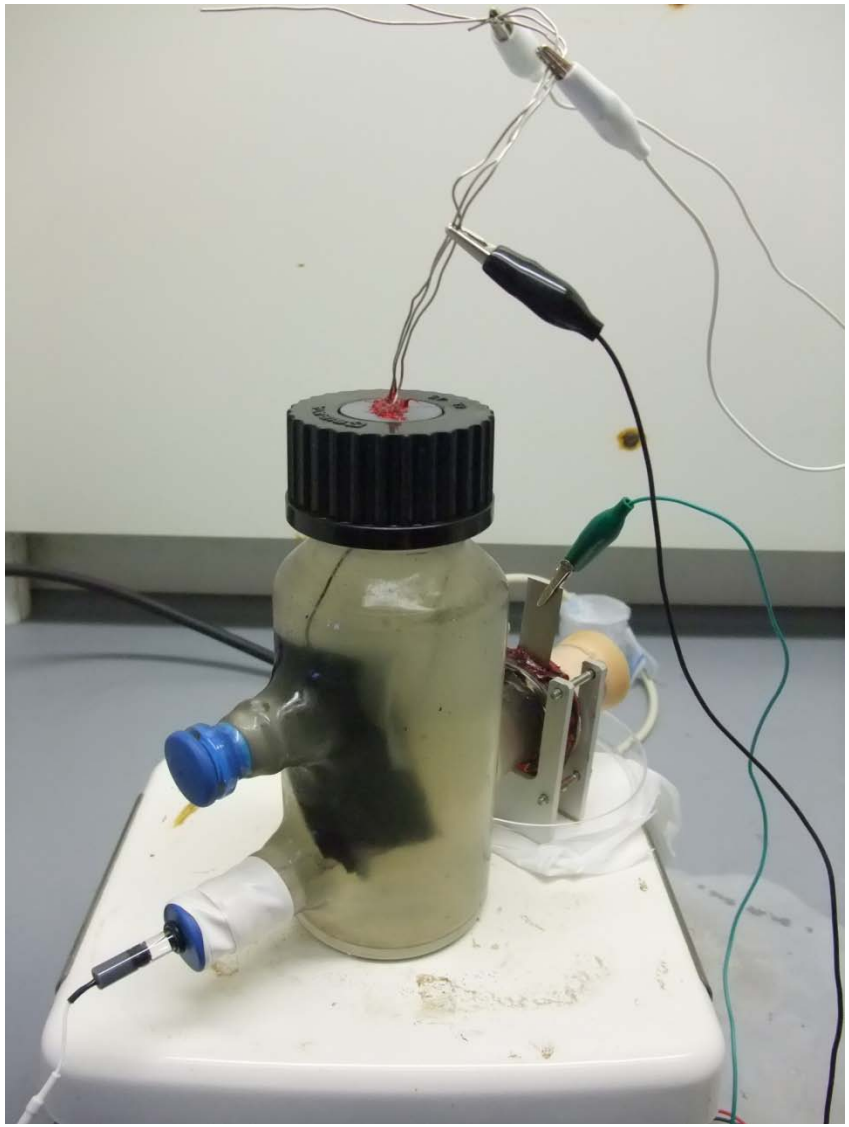
Fig.6) Enrichment of electricity-generating consortium by using actual primary clarifier in air-cathode microbial fuel cell at room temperature. Arrow: replacement to fresh primary clarifier, Arrowhead: replacement to the primary clarifier stored at 4° C.

Initial isolation of population capable of breaking down primarily clarifier – takes many days for stable population.

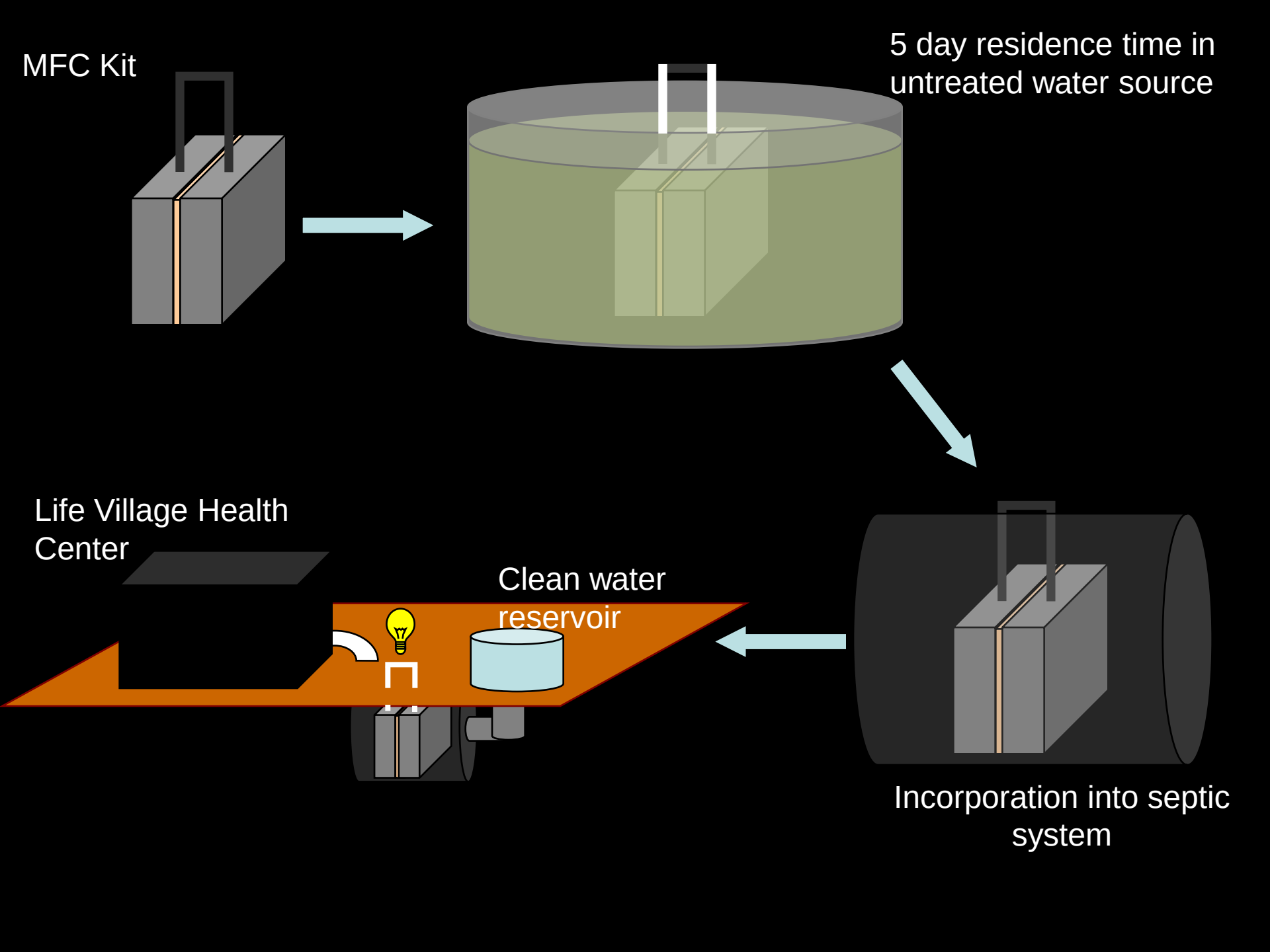
As population stabilizes, see about 20 different members – fairly simple community
Can store this community frozen for re-inoculation.



MFC with sewage waste water input: Day 1 ----- Day 10



Clean Water, Waste Disposal, Electricity !!!


MFC Kit
5 day residence time in untreated water source
Life Village Health Center
Clean water reservoir
Incorporation into septic system

Final Notes

Laguna Bacalar offers great opportunities

1. Basic science – stromatolites, evolution adaptation, etc.
2. Applied Science: learning how to protect our valuable resources and blend unique lake knowledge with the social and economic needs.

A great thank you to River Kaster and all who have contributed to this symposium –

a Great Start !!