Oil and Fossil Fuels

- Existing (coal, oil shale) and new potential energy Carbon-based alternatives (methane hydrates, coal to gas) pose continued environmental challenges.

- A reduction in CO₂ emissions is the main driver for renewable (CO₂-neutral) energy production.

Source: Scripps Institution of Oceanography (SIO), University of California, 1998.
Energy Utilization in the USA

- US energy use: 97 quad
- US electricity generation: 13 quad
- 5% used for W&WW: 0.6 quad
- Energy needed for H₂ for transportation:
  - Via electrolysis: 12 quad
  - Using new biomass process: 1.2 quad

97 quad [quadrillion BTUs] = 28,400 terawatt hours
Energy production: Needs to become more diverse and CO$_2$ neutral

- Solar
- Wind
- Biomass
  - Combustion: electricity
  - Conventional biotechnology: ethanol, methane, other value products
  - Novel biotechnological approaches: electricity and hydrogen
Energy can be recovered in many forms via biotechnological approaches

- **Methane**
  - Value: $0.43/kg-CH\textsubscript{4}
  - Elevated temperatures required for bioreactors
  - Need very long hydraulic detention times (big reactors)

- **Hydrogen**
  - Value: $6$/kg, $2.2 \times$ heat value of methane
  - Produced-low yield from fermentation from sugars
  - Produced from any biodegradable organic matter using the BEAMR process

- **Electricity**
  - Directly generated using microbial fuel cells
Renewable Energy Production

- Electricity production using microbial fuel cells

- Overcoming the “fermentation barrier”: high-yield $H_2$ production from biomass
Electricity Production in an Aqueous Cathode Microbial Fuel Cell

Bacteria-Driven Battery

- Microbial fuel cell powered by organic household waste
- Produces 8x as much energy as similar fuel cells and no waste
- Estimated cost - $15
- By 2005, NEC plans to sell fuel cell- powered computers
GASTROBOT (Gastro-Robot) – *a robot with a stomach*
U. South Carolina 2000.

*Uses an (MFC) system to convert carbohydrate fuel directly to electrical power without combustion*

Microbes from the bacteria (*E. coli*) decompose the carbohydrates (in food), releasing electrons. MFC output keeps Ni-Cd batteries charged, to run control systems/motors.

*“Gastronome” (2000)*
*“Chew-Chew” – meat-fueled Gastrobot*

The wagons contain a “stomach”, “lung”, gastric pump, “heart” pump, and a six cell MFC stack. Ti-plates, carbon electrodes, proton exchange membrane and a microbial biocatalyst, etc.
Material Requirements of a Biofuel cell

**biocatalysts** to convert chemical into electrical energy

(One can use biocatalysts, enzymes or even whole cell organisms)

**Substrates for oxidation:** Methanol, organic acids, glucose (organic raw materials as abundant sources of energy)

**Substrates for reduction at cathode:** Molecular oxygen or \( \text{H}_2\text{O}_2 \)

The extractable power of a fuel cell

\[
P_{\text{cell}} = V_{\text{cell}} \times I_{\text{cell}}
\]

**Kinetic limitations of the electron transfer processes, ohmic resistances and concentration gradients cause irreversible losses in the voltage (\( \eta \)).**

\[
V_{\text{cell}} = E_{\text{ox}} - E_{\text{fuel}} - \eta
\]

Where \( E_{\text{ox}} - E_{\text{fuel}} \) denotes the difference in the formal potentials of the oxidizer and fuel compounds.

Cell current controlled by electrode size, transport rates across Membrane.

**BUT** most redox enzymes do not transfer electrons directly.

Therefore, one uses electron mediators (relays).
Approach I: Fuel products (say hydrogen gas) are produced by fermentation of raw materials in the biocatalytic microbial reactor (BIOREACTOR) and transported to a biofuel cell.

The bioreactor is not directly integrated with the electrochemical part, allowing \( \text{H}_2/\text{O}_2 \) fuel cells to be conjugated with it.
Approach II: Microbiological fermentation can proceed in the anodic compartment itself.

It is a true biofuel cell! (not a combination of a bioreactor and a conventional fuel cell).

Hydrogen gas is produced biologically, but it is oxidized electrochemically in presence of biological components under milder conditions (than conventional Fuel cells) as dictated by the biological system.
Microbial Fuel Cell
(Schematic)

Metabolizing reactions in anode chamber are run anaerobically. An oxidation-reduction mediator diverts electrons from the transport chain. The MEDIATOR enters the outer cell lipid membranes and plasma wall, gathers electrons, shuttles them to the anode.
Why do we need Artificial Electron Relays (mediators)?

Reductive species produced by metabolic processes are isolated inside the intracellular bacterial space from the external world by a microbial membrane. Hence, direct electron transfer from the microbial cells to an anode surface is hardly possible!

Low-molecular weight redox-species (mediators) assist shuttling of electrons between the intracellular bacterial space and an electrode. To be efficient

a) Oxidized state of a mediator should easily penetrate the bacterial membrane;

b) Its redox-potential should be positive enough to provide fast electron transfer from the metabolite; and

c) Its reduced state should easily escape from the cell through the bacterial membrane.
Reduced form of mediator is cell-permeable and diffuses to the anode where it is electro-catalytically re-oxidized.

Cell metabolism produces protons in the anodic chamber, which migrate through a selective membrane to the cathodic chamber, are consumed by ferricyanide $[\text{Fe}^{3+}(\text{CN})_6]$ and incoming electrons, reducing it to ferrocyanide.

A cell-permeable mediator, in its oxidised form intercepts a part of NADH (Nicotinamide Adenine Dinucleotide) within the microbial cell and oxidizes it to NAD$^+$. 
Which Bacteria & Algae are used to produce hydrogen in bioreactors under anaerobic conditions in fuel cells?

Escherichia coli, Enterobacter aerogenes, Clostridium acetobutylicum, Clostridium perfringens etc.

The process is most effective when glucose is fermented in the presence of Clostridium butyricum (35 µmol h⁻¹ H₂ by 1g of microorganism at 37 C).

This conversion of carbohydrate is done by a multienzyme system:

Glucose + 2NAD⁺ \rightarrow \text{Multienzyme Embden–Meyerhof pathway} \rightarrow 2\text{Pyruvate} + 2\text{NADH}

Pyruvate + \text{Ferredoxin}_{ox} \rightarrow \text{Pyruvate–ferredoxin oxidoreductase} \rightarrow \text{Acetyl-CoA} + \text{CO}_2 + \text{Ferredoxin}_{\text{red}}

NADH + \text{Ferredoxin}_{ox} \rightarrow \text{NADH-ferredoxin oxidoreductase} \rightarrow \text{NAD}⁺ + \text{Ferredoxin}_{\text{red}}

\text{Ferredoxin}_{\text{red}} + 2H⁺ \rightarrow \text{Hydrogenase} \rightarrow \text{Ferredoxin}_{ox} + H₂
How do electrons reach the electrode?

Early evidence was that bacteria produced their own mediators:
- *Pseudomonas* spp. Produce mediators such as pyocyanin (Rabaey et al. 2004)
- Recent data suggests that *Shewanella* spp. use other methods…

Mediators produced by *Pseudomonas* spp. have distinct colors.
(Photo provided by Korneel Rabaey, Ghent University, Belgium; 2005).
Assembly of a simple MFC from a kit

1. Oxidizing reagent for cathode chamber. e.g. ferricyanide anion \([\text{Fe(CN)}_6]^{3–}\) from \(\text{K}_3\text{Fe(CN)}_6\) 10cm³ (0.02 M).

2. Dried Baker’s Yeast;

3. Methylene blue solution 5cm³ (10mM);

4. Glucose solution 5cm³ (1M).

Problems:
1. Ferricyanide does not consume liberated \(\text{H}^+\) ions (which lower pH levels).
2. Capacity of ferricyanide to collect electrons gets quickly exhausted.
To overcome this, ferricyanide can be replaced with an efficient oxygen (air) cathode which would utilize a half-reaction of:

\[ 6\text{O}_2 + 24\text{H}^+ + 24\text{e}^- \rightarrow 12\text{H}_2\text{O}, \]

d thereby consuming the H\(^+\) ions.
**Which microorganisms work best?**

*P. vulgaris* and *E. coli* bacteria are extremely industrious.

A monosaccharide (glucose) MFC utilizing *P. vulgaris* has shown yields of 50%–65%, while *E. coli* has been reported at 70%–80%.

An electrical yield close to the theoretical maximum has even been demonstrated using a disaccharide (sucrose $\text{C}_{12}\text{H}_{22}\text{O}_{11}$) substrate, although it is metabolized slower with a lower electron transfer rate than when using glucose.
Dyes function as effective mediators when they are rapidly reduced by microorganisms, or have sufficient negative potentials.

Thionine serves as a mediator of electron transport from *Proteus Vulgaris* and from *E. coli*.

- Phenoxazines (brilliant cresyl blue, gallocyanine, resorufin)
- Phenazines (phenazine ethosulfate, safranine),
- Phenothiazines (alizarine brilliant blue, *N,N*-dimethyl-disulfonated thionine, methylene blue, phenothiazine, toluidine blue), and
- 2,6-dichlorophenolindophenol, 2-hydroxy-1,4-naphthoquinone benzylviologen, are organic dyes that work with the following bacteria:
  - *Alcaligenes eutrophus*, *Anacystis nidulans*, *Azotobacter chroococcum*,
  - *Bacillus subtilis*, *Clostridium butyricum*, *Escherichia coli*, *Proteus vulgaris*,
  - *Pseudomonas aeruginosa*, *Pseudomonas putida*, and *Staphylococcus Aureus*, using glucose and succinate as substrates.

The dyes: phenoxazine, phenothiazine, phenazine, indophenol, thionine bipyridilium derivatives, and 2-hydroxy-1,4-naphthoquinone maintain high cell voltage output when current is drawn from the biofuel cell.
**Bacteria used in biofuel cells** when membrane-penetrating Electron Transfer Mediators (dyes) are applied

- *Alcaligenes eutrophus*
- *E. Coli (image width 9.5 μm)*
- *Anacystis nidulans 200 nm*
- *Proteus vulgaris*
- *Bacillus subtilis*
- *Pseudomonas putida*
- *Streptococcus lactis*
- *Pseudomonas aeruginosa*
Electrical wiring of MFCs to the anode using mediators.
(\textit{Co-immobilization of the microbial cells and the mediator at the anode surface})

(A) A diffusional mediator shuttling between the microbial suspension and anode surface is co-valently bonded. ‘1’ is the organic dye Neutral red.

(B) A diffusional mediator shuttling between the anode and microbial cells covalently linked (\textit{amide bond}) to the electrode. ‘2’ is Thionine.

(C) No diffusional mediator. Microbial cells functionalized with mediators. ‘The mediator ‘3’ i.e. TCNQ adsorbed on the surface of the microbial cell.'
MFCs using electron relays for coupling of intracellular electron transfer processes with electrochemical reactions at anodes

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Nutritional Substrate</th>
<th>Mediator</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pseudomonas methanica</em></td>
<td>$CH_4$</td>
<td>1-Naphthol-2- sulphonate indo 2,6-dichloro-phenol</td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td>Glucose</td>
<td>Methylene blue</td>
</tr>
<tr>
<td><em>Proteus vulgaris</em></td>
<td>Glucose</td>
<td>Thionine</td>
</tr>
<tr>
<td><em>Bacillus subtilis</em></td>
<td>Glucose</td>
<td>Thionine</td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td>Glucose</td>
<td>Thionine</td>
</tr>
<tr>
<td><em>Proteus vulgaris</em></td>
<td>Sucrose</td>
<td>Thionine</td>
</tr>
<tr>
<td><em>Lactobacillus plantarum</em></td>
<td>Glucose</td>
<td>Fe(III)EDTA</td>
</tr>
<tr>
<td><em>Escherichia coli</em></td>
<td>Acetate</td>
<td>Neutral Red</td>
</tr>
</tbody>
</table>
The redox cofactors *Nicotinamide Adenine Dinucleotide (NAD\(^+\))* and *Nicotinamide Adenine Dinucleotide Phosphate (NADP\(^+\))* play important roles in biological electron transport, and in activating the biocatalytic functions of dehydrogenases – the major redox enzymes.

Use of NAD(P)\(^+\)-dependent enzymes (e.g. lactate dehydrogenase; alcohol dehydrogenase; glucose dehydrogenase) in biofuel cells allows the use of lactate, alcohols and glucose as fuels. Biocatalytic oxidation of these substrates requires efficient electrochemical regeneration of NAD(P)\(^+\)-cofactors in the anodic compartment.
Current Density output from Microbial Fuel Cells is Low!

e.g.
1. Dissolved artificial redox mediators penetrate the bacterial cells, shuttle electrons from internal metabolites to anode. Current densities : 5–20 \( \mu \text{Acm}^{-2} \)

2. Metal-reducing bacteria (e.g. *Shewanella putrefaciens*) having special cytochromes bound to their outer membrane, pass electrons directly to anode. Current densities : maximum of 16 \( \mu \text{Acm}^{-2} \)

3. An MFC based on the hydrogen evolution by immobilized cells of *Clostridium butyricum* yielded short circuit currents of 120 \( \mu \text{Acm}^{-2} \) by using lactate as the substrate.

*But recently*


Using PANI modified Pt electrode immersed in anaerobic culture of *Escherichia coli* K12. CV response different for different stages of fermentation: a) sterile medium; b) exponential bacterial growth; and c) stationary phase of bacterial growth.
MFC Reactors

• **Aqueous-cathode MFCs:**
  – Salt Bridge proton exchange system
  – Membrane (Nafion)

• **Direct air cathodes MFCs:**
  – Single Chamber system for wastewater
  – Flat plate system
  – Small batch system for optimizing electricity generation

<table>
<thead>
<tr>
<th>Time</th>
<th>Power Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 yr</td>
<td>0.3 mW/m²</td>
</tr>
<tr>
<td>0.5 yr</td>
<td>2 mW/m²</td>
</tr>
<tr>
<td>1 yr</td>
<td>45 mW/m²</td>
</tr>
<tr>
<td>1.5 yr</td>
<td>500 mW/m²</td>
</tr>
<tr>
<td>Current</td>
<td>1500 mW/m²</td>
</tr>
</tbody>
</table>
Anaerobically growing suspension of E.coli K12 in glucose in the Reactor. Bacterial Medium pumped thru anode compartment. Anode is woven graphite cloth, platinized, And PANI-modified.

Cathode is unmodified woven graphite. Catholyte (50 mm ferricyanide solution in a phosphate buffer). Nafion proton conducting membrane separates anode and cathode compartments.

Open circuit potential: 895 mV.
Steady state 30 mA under short circuit conditions.
Max. currents measured: 150 mA
Max. power output: 9 mW.

Operates a ventilator driven by 0.4 V motor, continuously.
Operation costs low.
Electricity from Direct Oxidation of Glucose in Mediatorless MFC

The device doesn’t need toxic/expensive mediators because the bacteria *Rhodoferax ferrireducens* attach to the electrode’s surface and transfer electrons directly to it.

The microbe (isolated from marine sediments in Va., USA) metabolizes Glucose/sugars into CO$_2$ producing e’s.

80% efficiency for converting sugar into electricity.
Graphite electrode is immersed into a solution containing glucose and the bacteria. The microbe *R. ferrireducens* is an "iron breather" – microorganisms which transfer electrons to iron compounds. It can also transfer electrons to metal-like graphite.

*R. ferrireducens* can feed on organic matter (sugar), and harvest electrons.

The prototype produced 0.5 V, enough to power a tiny lamp. A cup of sugar could power a 60-W light bulb for 17 hours.

But, the generation of electrons by bacteria is too slow to power commercial applications. Increasing the contact surface of electrode (making it porous) may bring in more bacteria in contact.
Harnessing microbially generated power on the seafloor

Seafloor has sediments meters thick containing 0.1-10% oxidizable organic carbon by weight – an immense source of energy reserve. Energy density of such sediments assuming 2% organic carbon content and complete oxidization is $6.1 \times 10^4$ J/L (17 W h/L), – a remarkable value considering the sediment volume for the Gulf of Mexico alone is $6.3 \times 10^{14}$ liters.

Microorganisms use a bit of this energy reserve (limited by the oxidant supply of the overlying seawater), and thus create a voltage drop as large as 0.8 V within the top few mm’s to cm’s of sediment surfaces.

This voltage gradient across the water-sediment interface in marine environments can be exploited by a fuel cell consisting of an anode embedded in marine sediment and a cathode in overlying seawater to generate electrical power *in situ.*

MFCs could power devices located at the bottom of the ocean, where the bacteria would feed on sugar-containing sediments.
**Geobacters** have novel electron transfer capabilities, useful for bioremediation and for harvesting electricity from organic waste.

First geobacter, known as *Geobacter metallireducens*, (strain GS-15) discovered in 1987 was found to oxidize organic compounds to CO₂ with iron oxides as the electron acceptor.

i.e. *Geobacter metallireducens* gains its energy by using iron oxides in the same way that humans use oxygen. It may also explain geological phenomena, such as the massive accumulation of magnetite in ancient iron formations.

*Geobacters* in Boston Harbor sediments colonize electrodes placed in the mud to power a timer.
Geobatteries powering a calculator

*Geobacter* colonizing a graphite electrode surface
Fuel cells convert chemical energy directly to electrical energy. Reduced fuel is oxidized at anode – transferring electrons to an acceptor molecule, e.g., oxygen, at cathode.

Fuel cell with hydrogen gas as fuel and oxygen as oxidant ↓

Oxygen gas when passed over cathode surface gets reduced, combines with H\(^+\) ions (produced electrochemically at anode) arriving at cathode thru the membrane, to form water.

One needs:
- An electrolyte medium;
- Catalysts;
- Ion-exchange membrane;
  (to enhance rate of reaction),
  (to separate the cathode and anode compartments).
Examples of microbial-based biofuel cells utilizing fermentation products for their oxidation at anodes

<table>
<thead>
<tr>
<th>Microorganism</th>
<th>Nutritional substrate</th>
<th>Fermentation Product</th>
<th>Biofuel cell voltage</th>
<th>Biofuel cell current or current density</th>
<th>Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Clostridium butyricum</em></td>
<td>Waste water</td>
<td>H$_2$</td>
<td>0.62 V (at 1 Ω)</td>
<td>0.8 A (at 2.2 V)</td>
<td>Pt-blackened Ni, 165 cm$^2$ (5 anodes in series)</td>
</tr>
<tr>
<td><em>Clostridium butyricum</em></td>
<td>Molasses</td>
<td>H$_2$</td>
<td>0.66 V (at 1 Ω)</td>
<td>---</td>
<td>Pt-blackened Ni, 85 cm$^2$</td>
</tr>
<tr>
<td><em>Clostridium butyricum</em></td>
<td>Lactate</td>
<td>H$_2$</td>
<td>0.6 V (oc)$^d$</td>
<td>120 μA cm$^{-2}$ (sc)$^e$</td>
<td>Pt-black, 50 cm$^2$</td>
</tr>
<tr>
<td><em>Enterobacter aerogenes</em></td>
<td>Glucose</td>
<td>H$_2$</td>
<td>1.04 V (oc)</td>
<td>60 μA cm$^{-2}$ (sc)</td>
<td>Pt-blackened stainless steel, 25 cm$^2$</td>
</tr>
<tr>
<td><em>Desulfovibrio desulfuricans</em></td>
<td>Dextrose</td>
<td>H$_2$S</td>
<td>2.8 V (oc)</td>
<td>1 A</td>
<td>Graphite, Co(OH)$_2$ impregnated (3 anodes in series)</td>
</tr>
</tbody>
</table>
Electron-relays are needed for efficient electrical "wiring" of redox enzymes
Integrated microbial biofuel cells producing electrochemically active metabolites in the anodic compartment of biofuel cells

**Microbial cells producing H₂ during fermentation immobilized directly in the anodic compartment of a H₂/O₂ fuel cell**

A rolled Pt-electrode was introduced into a suspension of *Clostridium butyricum* microorganisms. Fermentation conducted directly at the electrode, supplying anode with H₂ fuel. Byproducts of the fermentation process (hydrogen, 0.60 mol; formic acid, 0.20mol; acetic acid, 0.60mol; lactic acid, 0.15 mol) could also be utilized as fuel. For example, pyruvate produced can be oxidized:

\[
\text{Pyruvate} \rightarrow \text{Pyruvate-formate lyase} \rightarrow \text{Formate}
\]

Metabolically produced formate is directly oxidized at the anode when the fermentation solution passes the anode compartment:

\[
\text{HCOO}^- \rightarrow \text{CO}_2 + \text{H}^+ + 2e^- \text{ (to anode)}
\]

The biofuel cell that included *ca.* 0.4 g of wet microbial cells (0.1 g of dry material) yielded the outputs \( V_{\text{cell}} = 0.4 \text{V} \) and \( I_{\text{cell}} = 0.6 \text{mA} \).
Methanol/dioxygen biofuel cell, based on enzymes (producing NADH upon biocatalytic oxidation of primary substrate) and diaphorase (electrically contacted via an electron relay and providing bioelectrocatalytic oxidation of the NADH to NAD$^+$

Enzymes:
ADH: alcohol dehydrogenase
AlDH: aldehyde dehydrogenase
FDH: formate dehydrogenase

NAD$^+$-dependent dehydrogenases oxidize CH$_3$OH to CO$_2$; diaphorase (D) catalyzes the oxidation of NADH to NAD$^+$ using benzylviologen, BV$^{2+}$ ($N,N'$-dibenzyl-4,4-bipyridinium) as the electron acceptor.
BV$^+$ is oxidized to BV$^{2+}$ at a graphite anode and thus, releases electrons for the reduction of dioxygen at a platinum cathode. The cell provided $V_{oc} = 0.8$ V and a maximum power density of ca. 0.68 mW cm$^{-2}$ at 0.49 V.
Viability of Robots working on MFCs

Main source of energy in plants is carbohydrates in the form of sugars and starches. Foliage most accessible to robots such as spinach, turnip greens, cabbage, broccoli, lettuce, mushroom, celery and asparagus may contain about 4% carbohydrate by weight.

The energy content of carbohydrate is around 5 kcal/g (=21 kJ/g). This amounts to 0.82 kJ/ml for liquified vegetable matter, similar to the energy density of a Lithium-ion battery. If converted into an electrical form this would yield 5 kWh/kg for a pure monosaccharide sugar, or 0.2 kWh per liter of liquified vegetable matter.
Renewable Energy Production

• Electricity production using microbial fuel cells

• Overcoming the “fermentation barrier”: high-yield H₂ production from biomass
Current sources for H₂ Production

- Electrolysis: 4%
- Coal: 18%
- Natural Gas: 48%
- Heavy oils and naphtha: 30%
**Observation:** H₂ production results primarily from sugars

**Biogas:**
- 60% H₂
- 40% CO₂

H₂ yields: Increase by CO₂ removal

H₂ Yield increased by 43% with CO₂ scrubbing

**Observation:** Lots of waste products, and not enough acetic acid (best for $\text{H}_2$ production)
**Observation**: the “fermentation barrier”

Maximum: 12 mol-H$_2$/mol-hexose

- $\text{C}_6\text{H}_{12}\text{O}_6 + 2 \text{H}_2\text{O} \rightarrow 4 \text{H}_2 + 2 \text{C}_2\text{H}_4\text{O}_2 + 2 \text{CO}_2$

Maximum of 4 mol/mol (2 mol/mol in practice)

How can we recover the remaining 8 to 10 mol/mol?
Overcoming the “Fermentation Barrier”

• **Bio-Electrochemically Assisted Microbial Reactor (BEAMR)** [Process developed with Ion Power, Inc.]:
  - Acetate: achieve 2.9 mol-H$_2$/mol-acetate (Maximum of 4 mol/mol)
  - Couple fermentation + BEAMR process → 8 to 9 mol-H$_2$/mole glucose
  - Not limited to glucose
Essentials of the BEAMR Process

• Conventional MFC:
  • Anode potential = -300 mV
  • Cathode Potential = +200 mV (+804 mV theory)
  • Circuit working voltage = -(-300) + 200 = 500 mV

  \[
  \begin{align*}
  \text{Anode:} & \quad \text{C}_2\text{H}_4\text{O}_2 + 2 \text{H}_2\text{O} \rightarrow 2 \text{CO}_2 + 8 \text{e}^- + 8 \text{H}^+ \\
  \text{Cathode:} & \quad \text{O}_2 + 4 \text{H}^+ + 4 \text{e}^- = 2 \text{H}_2\text{O}
  \end{align*}
  \]

• BEAMR Process: No oxygen
  • Anode potential = -300 mV
  • Cathode potential: 0 mV
  • Needed to make H\textsubscript{2} = 410 mV (theory)
  • Circuit (300 mV) augmented with >110 mV = >410 mV

  \[
  \begin{align*}
  \text{Anode:} & \quad \text{C}_2\text{H}_4\text{O}_2 + 2 \text{H}_2\text{O} \rightarrow 2 \text{CO}_2 + 8 \text{e}^- + 8 \text{H}^+ \\
  \text{Cathode:} & \quad 8 \text{H}^+ + 8 \text{e}^- \rightarrow 4 \text{H}_2
  \end{align*}
  \]
**BEAMR Process**

**Cathode**
- CO₂
- e⁻
- H₂

**Anode**
- Bacteria

**PS**
- e⁻

**Cathode chamber is kept anaerobic**

Minimum voltage needed is >0.25 V (0.11 V theory)

Hydrogen Recovery

60%-78% Coulombic Efficiency (electron recovery)

>90% $\text{H}_2$ recovery

-Overall:

2.9 mol-$\text{H}_2$/mol-acetate

**Observation 1:** Industries currently “throw away” a valuable resource (land application)
Observation 2: Other countries are investing in development and scale-up of hydrogen and alternative energy processes

Large-scale biohydrogen reactor being tested at Harbin University, China
(Director: Prof. Nanqi Ren)
Thank You

Microbes make the world go around

Marvellous microbes