Bio-Electricity for Space Exploration

PI: Matthew Silver
Co-I: Kranthi Vistakula

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IntAct Labs LLC
What is Bio-Electricity?

- Electrical Power Critically Constrains Space Missions
- Many Biological Molecules and Microbes have Interesting Electrical Properties
- These can and have been studied and exploited
  - Biological Solar Cells, Microbial Fuel Cells
- Biological Power Systems can Revolutionize Space Exploration

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Presentation Outline

1. Project Overview

2. Database and Design Space

3. Application and Research Areas
   a. Microbial Fuel Cells
   b. Power Skins

4. Conclusions and Phase II Goals
Team

Int·Act Labs LLC
- Matthew Silver, Principal Investigator
- Kranthi Vistakula, Co-Investigator
- Ned Calder, Project Manager

Payload Systems Inc
- Joe Parrish (Space Systems Design)
- Liping Sun (Bio-culturing)
- Edison Guerra (Machining, Fabrication)

Additional Thanks To
- Professor Jeff Hoffman, Space Systems Lab
- Professor Tom Knight, CSAIL and Synthetic Bio
- Noah Taylor, Biology Department
- Yarling Tu, Biology Department
- Jon Halpert, MIT Chemical Engineering
- Derek Lovely, UMass Amherst
- Chris Lund, Images and Visualizations

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Bio-Electric Space Exploration Research Summary

• **Vision:**
  New space power paradigm based on biological molecules and mechanisms. From Mechanisms to Architectures.

• **Disciplines:**
  Biotechnology, Synthetic Biology, Electrical Engineering, Space Systems Design.
A New Paradigm for Space Power

Current Power Paradigm

• Silicon-Base Solar Voltaic
• Windmills
• H₂ or CH₄ Fuel Cells
• Nuclear Thermal, RTG
• Li Batteries

• Complex Manufacturing
• Degrade with Time
• Labor-Intensive Repair
• Large, Bulky
• Inflexible once in mission

Bio-Electric Power Paradigm

• Biological Solar Voltaic
• Piezo Electric Protein Skins
• Microbial Fuel Cells
• Electric Greenhouses
• Photo-Active Fuel Cells

• Growable, Scalable Power
• Self-Healing Systems
• “Throw-away” power sources
• High P/W Energy Scavenging
• Unified Life Support & Power

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# Database: Biological Components

<table>
<thead>
<tr>
<th>Class/Genus</th>
<th>Description</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhodopsins</td>
<td>Photo-Active membrane protein</td>
<td>Solar Radiation: 450-700nm, 560nm peak)</td>
<td>Electrochemical gradient, H⁺, Cl⁻</td>
</tr>
<tr>
<td>Prestin</td>
<td>Mechano-Sensitive membrane protein</td>
<td>Pressure, Vibration &lt; 100 kHz</td>
<td>Electrochemical gradient Cl⁻</td>
</tr>
<tr>
<td>Transient Receptor Potential Proteins</td>
<td>Heat-Activated ion channel</td>
<td>Temperature activation threshold</td>
<td>Electrochemical Grandient, Ca⁺</td>
</tr>
<tr>
<td>Geobacter</td>
<td>Iron Reducing electrigen microbe</td>
<td>Acetate, aromatic compounds</td>
<td>CO₂, electrons</td>
</tr>
<tr>
<td>Rhodoferax</td>
<td>Iron Reducing electrigen microbe</td>
<td>Lactates, acetates</td>
<td>CO₂, electrons, other products</td>
</tr>
<tr>
<td>Geobacter Pili</td>
<td>Microbial Nano-Wire proteins</td>
<td>electrons</td>
<td>electrons</td>
</tr>
</tbody>
</table>
From Molecules and Microbes to Applications

- Microbial Fuel Cell, Bio-Electric Chamber
- Dual Photo-Active/Organic Microbial Fuel Cell
- Piezo-Electric Skin
- Biological Solar Cell
- Charge Storage Device, Ultra-Capacitor

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From Molecules and Microbes to Applications

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Presentation Outline

1. Create Database
2. Select Application Areas
   - Power Skin Conceptual Design, Experiments
4. Phase II Detailed Prototypes System Architectures

Microbial Fuel Cell, Bio-Electric Chamber

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Application Area 1: Microbial Fuel Cells

- **Applications:**
  - Life-Support and Power Production; Electric Greenhouses; Growable Solar Power

- **Electricigen Microbes**
  - Single Strain *(3.6 W/m²)* [Lovely, 2006]
  - Extant Communities *(4.3 W/m²)* [Rabaey, 2005]
  - Controlled, Tailored Communities (Goal)

![Diagram of Microbial Fuel Cells](image)

Geobacter

Rhodoferax on an electrode

Batch-Mode Microbial Fuel Cells at IntAct Labs
## Upper Bound Power Estimate

<table>
<thead>
<tr>
<th>Waste Streams</th>
<th>Kg/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Human Waste</td>
<td>0.72</td>
</tr>
<tr>
<td>Inedible Plant Biomass</td>
<td>5.45</td>
</tr>
<tr>
<td>Trash</td>
<td>0.556</td>
</tr>
<tr>
<td>Packaging Material</td>
<td>2.017</td>
</tr>
<tr>
<td>Paper</td>
<td>1.164</td>
</tr>
<tr>
<td>Tape</td>
<td>0.246</td>
</tr>
<tr>
<td>Filters</td>
<td>0.326</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>0.069</td>
</tr>
<tr>
<td><strong>Organic Waste Stream</strong></td>
<td><strong>10.55</strong></td>
</tr>
</tbody>
</table>


### Interplanetary Transit

1. One Crew + Trash: **2.5 kW-hrs/Day (~100W)**
2. Six Person Crew + Trash + Biomass: **29.7 kW-hours/Day (~1 kW)**
3. CO₂ Recycled to Algal Growth: 1kg of algae ~ **4 kW-hrs (150W)**

### Growing Power on Mars

1. High-Rate Algal Growth: **0.025 kg/M² Day (earth) 6x on mars**
2. Algal Field: ~ **2-4 times power per area of solar cell + O₂**
3. Casing: Protein-Based Plastics
4. Photo-Fuel Cell Possible with Electron Mediators (cyanophyta species)

\[
\begin{align*}
C_6H_{12}O_6 + 6H_2O &\rightarrow 6CO_2 + 24H^+ + 24e^- & E^0 = 0.0014V \\
6O_2 + 24H^+ + 24e^- &\rightarrow 12H_2O & E^0 = 1.23V
\end{align*}
\]

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Developing Bio-Electric Chambers for Space

- **Synergies** with other bio-electric apps (Geobacter species)

- **Full Oxidation** of organics (*Catabolic Engineering*)

- **Flow-Through** Bioreactor Design (*Tubular Form*)

- **Zero, Low-G:** Functionality (*Membrane Biofilm*)

- **Increase:** Anode surface area (*Fractal surfaces, Gold Nano-particles*)

- **Increase:** Respiration rates (*Genetic Engineering*)

- **Fully Growable Systems:** Bio-fabricating *growth chambers* (*bio polymers*)

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Potential Full Reduction Pathways
Bio-Chambers in Life Support

1. Pre-Treatment
2. Hydrolysis

Glucose Amino Acid

Clostridia species

Acetate \( \text{C}_2\text{H}_4\text{O}_2 \)

Geobacter Species

Fatty Acids

Aromatic Compounds

\( \text{CO}_2 \)

Phototrophic Bacteria or Algae

• Inputs
  – Waste
  – Biomass
  – \( \text{CO}_2 \)

• Outputs
  – Electricity
  – Oxygen

Solid Wastes

Plant Biomass

Roots

Paper, etc

Astronaut \( \text{CO}_2 \)

Martian Air (\( \text{CO}_2 \))

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Flow-Through Bio-Reactor Design

Membrane Biofilm Reactor

Sizing Model For Flow Through
Example Result: At 5 W/m², 0.5 cm tube → 1kw ~ 1/3 m³

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Experiment 1: Microbial Fuel Cell Anode Optimization

• **Objective:**
  – Test fractal anode surface structure; Gold Nanoparticles; Gold Foam
  – Test Chamber for Photo-active Geobacter sulf.

• **Motivation:**
  – Quantify power output, fractal anode design:
  – Gold Nano-Particles (fractal area), Gold Foam
  – Verify and Estimate power output G. sulfurreducens
  – Test Chamber for Experiment 3

• **Methods**
  – Geobacter sulfurreducens
  – Single-chamber, Batch Mode MFC
  – Carbon Cloth Air Cathode
  – PEM: Dupont Nafion® 117

• **Progress**
  – MFC Fabricated, G. sulf. Cultured, Anodes Fabricated

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Experiment 2: Expression of Rhodopsin in Geobacter

- **Objective**
  - Express of rhodopsin (photoactive proton pump) in Geobacter (microbial fuel cell species)

- **Motivation**
  - Initial step towards coupling rhodopsin proton pump with unique Geobacter electron transport proteins (pili)
  - Photo-activated metabolic change

- **Methods**
  - Standard Protein Expression and Verification
  - Photo-activated experiments in prototype microbial fuel cells

- **Progress**: Source cultured, vectors created

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>spectrophotometer (membrane absorption)</td>
</tr>
<tr>
<td>2</td>
<td>Protein expression (Western blot)</td>
</tr>
<tr>
<td>3</td>
<td>Microbial Photo-reaction (Microbial Fuel Cell)</td>
</tr>
</tbody>
</table>
Presentation Outline

1. Create Database
2. Select example applications
4. Phase II Detailed Prototypes System Architectures

Power Skin Conceptual Design Experiments

Piezo-Electric Skin

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Application and Research Area II: Bio-Electric Power-Skin

- **Goal**: Novel energy scavenging skin based on ionic potential difference created by membrane proteins

- **Specific Benefits**
  - Abundant source of ‘free’ energy
  - Orders of magnitude more sensitive than inorganic materials
  - Proteins have high power to weight ratios
  - Architecture applies to other mechanisms:
    - Examples: thermal active, photoactive

- **Applications**
  - Distributed sensors, EVA, space habitats
Sources of Power

• **Martian Wind**
  – Pressure, Piezoelectric micro-turbines
  – Similar wind speeds to Earth, but lower density
    \(0.022 \text{ kg/m}^3\)
  
  \[ P = \frac{1}{2} \rho A v^3 \]
  
  *assume*: \(7 \text{ m/s} \rightarrow 3 \text{ W/m}^2\)

• **Mechanical or ambient structural vibrations**
  – Developing general model
  – Example: Vibrating Machinery
    • Observed vibrations at 120hz & acceleration of \(2.25 \text{ m/s}^2\)
    
    \[ P = \frac{m \zeta c_\omega^2 (\omega/\omega_n)^3 Y^2}{(2 \zeta_T \omega/\omega_n) + (1 - ((\omega/\omega_n)^2)^2)} \]
    
    \[ P = 0.1 \text{ W} \]

• **Electrical Potential**
  – 3 Chloride Ions Separated each Vibration
  
  \[ P = E j * f = \frac{1}{2} C V^2 f \]
Potential Applications

- **Distributed Sensing**
  - ~100 µW/node
  - Continuous Power Scavenging
  - “Throw-away” power source

- **EVA**
  - Surface area ~ .7 m²
  - Power on the order 1 W
  - Multiple Sensors without Wiring

- **Large Scale Skin**
  - Planned Mars structures/domes (d~30m) surface area ~3000 m²
  - Power on the order 1 kW
Scaling and Optimization

- **Approaches to Scaling**
  - Flexible Electrodes
  - Micro channels
    - Lipid bilayers with protein are embedded into micro channels
  - Liposomes
    - Liposome's sandwiched between electrodes

- **Redox reactions**
  - Conversion of ionic potential into electric potential using re-do-x mechanisms

- **Optimization**
  - Increase Protein Output
  - Genetic engineering
  - Skin Robustness
Powerskin Prototype

- **Objective**
  - Measuring power output by developing a Prestin force sensor

- **Procedure**
  - Express and purify Prestin
  - Incorporate Prestin in tethered lipid bilayer
  - Construct sensor
  - Measure potential difference generated

- **Progress**
  - Sensor architecture developed
  - cDNA of Prestin acquired from Dallos Lab of Northwestern University
  - Expression and purification experiments are in process
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Phase I Accomplishments

- **Vision:** New space power paradigm based on biological molecules and mechanisms. From Mechanisms to Architectures.

- **Database**
  Design space categorized; Database created and made accessible online

- **Bio-Electric Chambers**
  Conceptual design and architecture; Calculated estimated power levels; Prototype Batch-Mode Reactor built
  **Remaining:** Data Collection; Rhodopsin Experiment

- **Power Skins**
  Conceptual design and architecture developed; Calculated estimated power levels; Prototype bio-sensor began
  **Remaining:** Power Model; Patch Clamp Biosensor Experiment

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Phase II

- **Systems Architecture**
  - Integrate component architectures into systems level architecture

- **Component Development**
  - Combined Algal Fuel Cells (solar power) with MFC

- **Microbial Fuel Cell Development:**
  - Develop and test compact flow-through MFC for zero and low G
  - Elaborate Bio-polymer—grow able solar cell concept

- **Power Skin Scaling**
  - Test scaling mechanism for power skin
  - Synthesize structural, environmental control proteins into power skin
Questions?

IntAct Labs LLC
247 Third Street
Cambridge, MA 02142

Email: info@intactlabs.com
Phone: 617 995 5675
Fax: 617 868 6682