Bio-Electricity for Space Exploration

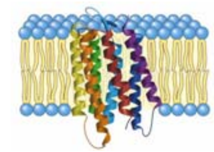
PI: Matthew Silver
Co-I: Kranthi Vistakula

Presentation to the NIAC Conference
March 6, 2007

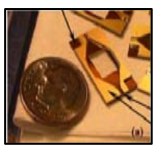
IntAct Labs LLC

What is Bio-Electricity?

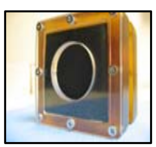
- **Electrical Power Critically Constrains Space Missions**



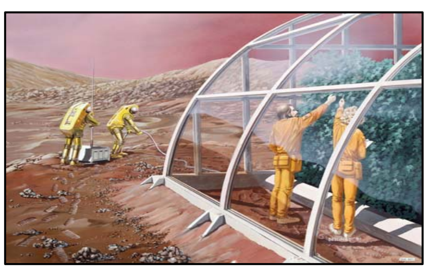
- **Many Biological Molecules and Microbes have Interesting Electrical Properties**



- **These can and have been studied and exploited**
  - Biological Solar Cells, Microbial Fuel Cells



- **Biological Power Systems can Revolutionize Space Exploration**



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

IntAct 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)

MIT

- Professor Jeff Hoffman, Space Systems Lab
- Professor Tom Knight, CSAIL and Synthetic Bio
- Noah Taylor, Biology Department
- Yarling Tu, Biology Department

Additional Thanks To

- Jon Halpert, MIT Chemical Engineering
- Derek Lovely, UMass Amherst
- Chris Lund, Images and Visualizations

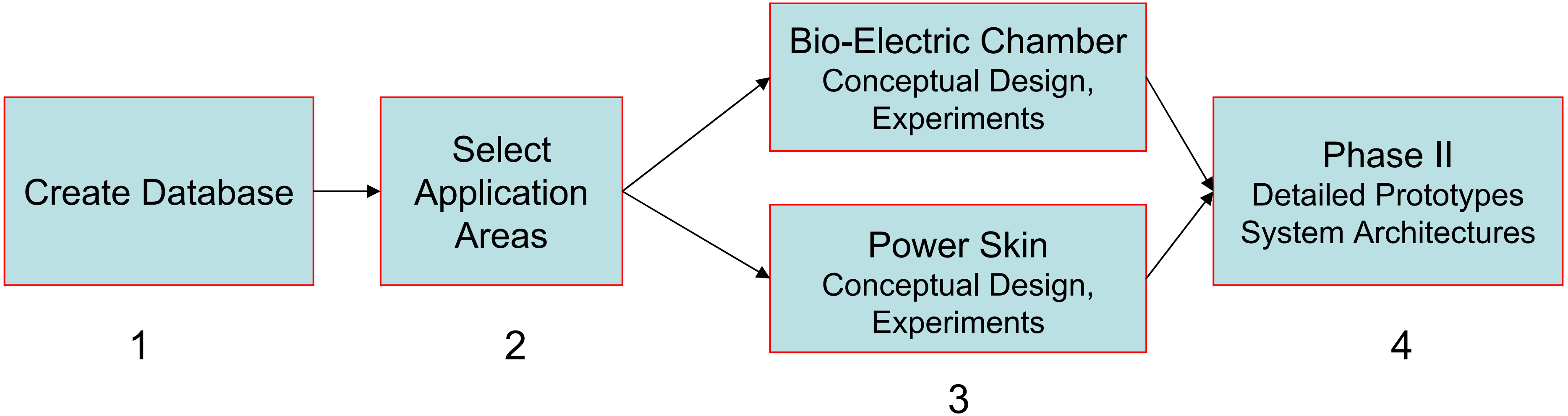
Bio-Electric Space Exploration Research Summary

- **Vision:**

  New space power paradigm based on biological molecules and mechanisms. From Mechanisms to Architectures.

- **Disciplines:**

  Biotechnology, Synthetic Biology, Electrical Engineering, Space Systems Design.



 Cambridge, MA

A New Paradigm for Space Power

Current Power Paradigm

- Silicon-Base Solar Voltaic
- Windmills
- H_2 or CH_4 Fuel Cells
- Nuclear Thermal, RTG
- Li Batteries

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

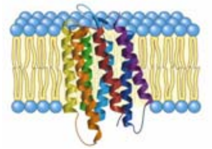
Bio-Electric Power Paradigm

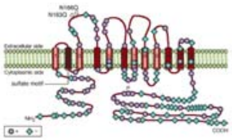
- Biological Solar Voltaic
- Piezo Electric Protein Skins
- Microbial Fuel Cells
- Electric Greenhouses
- Photo-Active Fuel Cells

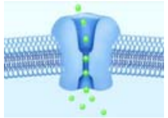
- Growable, Scalable Power
- Self-Healing Systems
- “Throw-away” power sources
- High P/W Energy Scavenging
- Unified Life Support & Power

Fully Inorganic → Fully Biological

Database: Biological Components







Class/Genus	Description	Input	Output
Rhodopsins	Photo-Active membrane protein	Solar Radtion: 450-700nm, 560nm peak)	Electrochemical gradient, H^+, Cl^-
Prestin	Mechano-Sensitive membrane protein	Pressure, Vibration < 100 kHz	Electrochemical gradient Cl^-
Transient Receptor Potential Proteins	Heat-Activated ion channel	Temperature activation threshold	Electrochemical Grandient,Ca^+
Geobacter	Iron Reducing electrigen microbe	Acetate, aromatic compounds	CO_2, electrons
Rhodoferax	Iron Reducing electricigen microbe	Lactates, acetates	CO_2, electrons, other products
Geobacter Pili	Microbial Nano-Wire proteins	electrons	electrons

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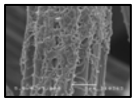
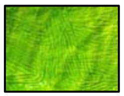
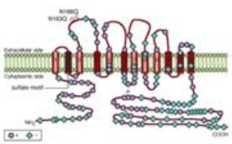
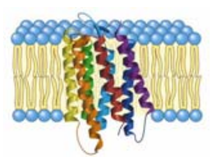
From Molecules and Microbes to Applications

  → Microbial Fuel Cell, Bio-Electric Chamber

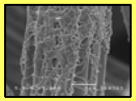
  → Dual Photo-Active/Organic Microbial Fuel Cell

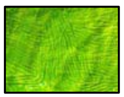
 → Piezo-Electric Skin

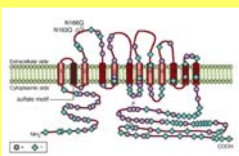
 → Biological Solar Cell

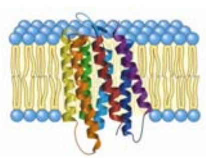
 → Charge Storage Device, Ultra-Capacitor

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

Presentation Outline

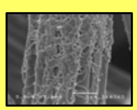
Create Database
1

Select Application Areas
2

Bio-Electric Chamber
Conceptual Design, Experiments

Power Skin
Conceptual Design, Experiments
3

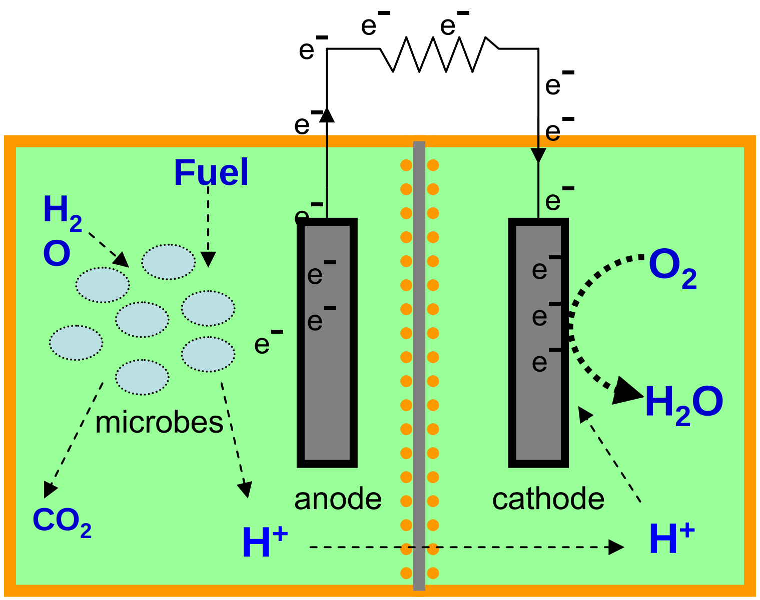
Phase II
Detailed Prototypes
System Architectures
4

→ Microbial Fuel Cell, Bio-Electric Chamber

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)



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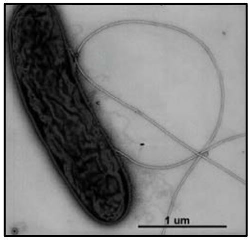
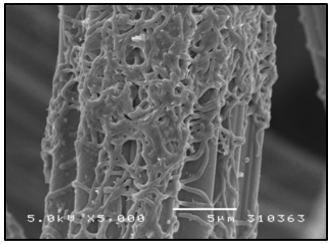
selective membrane

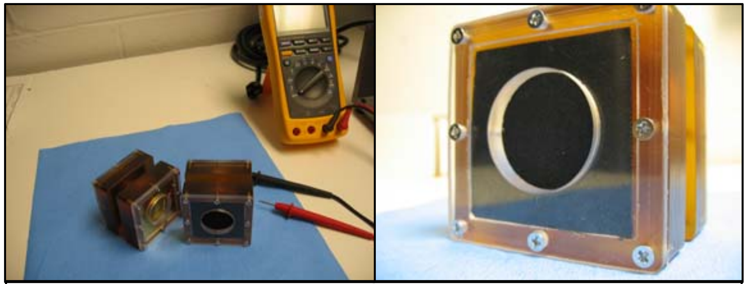




Courtesy: Geobacter.org

Geobacter

Rhodoferax on an electrode



Batch-Mode Microbial Fuel Cells at IntAct Labs

Upper Bound Power Estimate

Waste Streams	Kg/day
Dry Human Waste	0.72
Inedible Plant Biomass	5.45
Trash	0.556
Packaging Material	2.017
Paper	1.164
Tape	0.246
Filters	0.326
Miscellaneous	0.069
Organic Waste Stream	**10.55**

Estimated wastes for low-carb diet exploration mission. Crew size = 6
(NASA Waste Processing and Resource Recovery Workshop)

$$C_6H_{12}O_6 + 6H_20 \rightarrow 6CO_2 + 24H^+ + 24e^- \qquad E^0 = 0.0014V$$

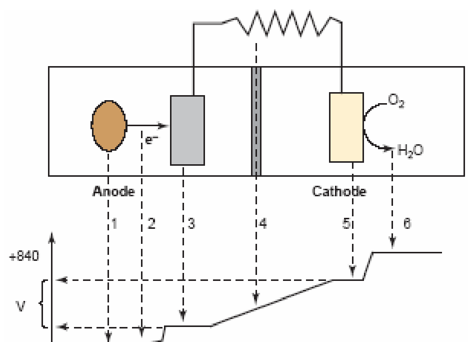
$$6O_2 + 24H^+ + 24e^- \rightarrow 12H_20 \qquad E^0 = 1.23V$$

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. $C0_2$ Recycled to Algal Growth: 1kg of algae ***~ 4 kW-hrs (150W)***

Growing Power on Mars

1. High-Rate Algal Growth: **0.025 kg/M^2 Day (earth) 6x on mars**
2. Algal Field: **~ 2-4 times power per** area of solar cell + **0_2**
4. Casing: Protein-Based Plastics
3. Photo-Fuel Cell Possible with Electron Mediators (cyanophyta species)



Losses (Rabaey, 2004)

$CO_2 + H_20$ + Sunlight →  → electricity + 0_2

$(C_6H_{12}0_5)_n$

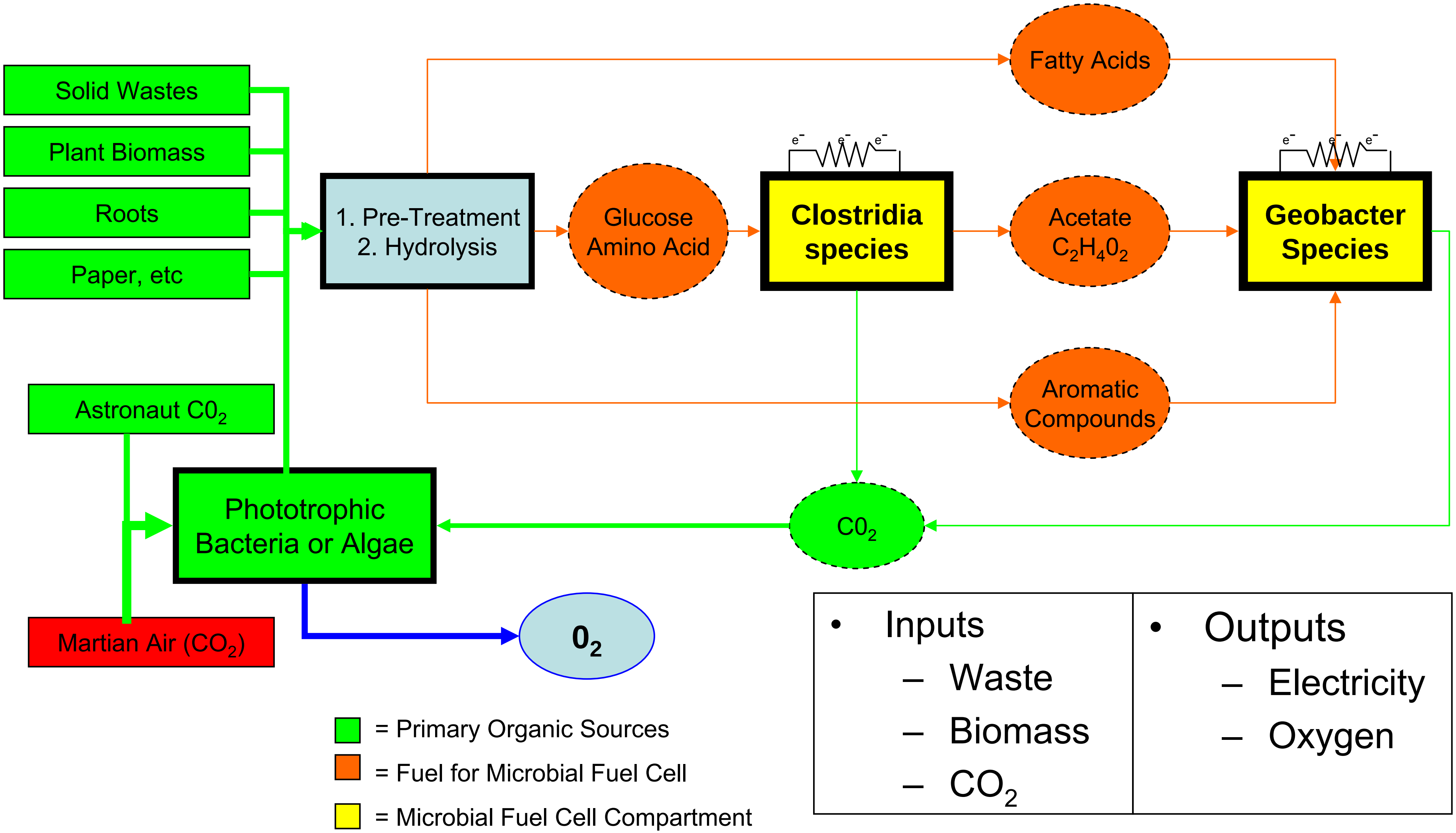
Cambridge, MA

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)*

Potential Full Reduction Pathways

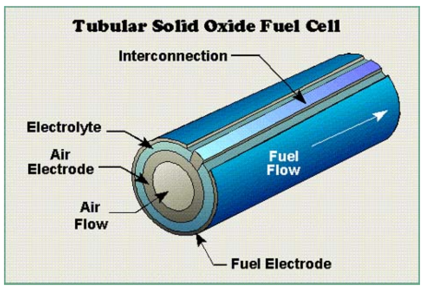
Bio-Chambers in Life Support



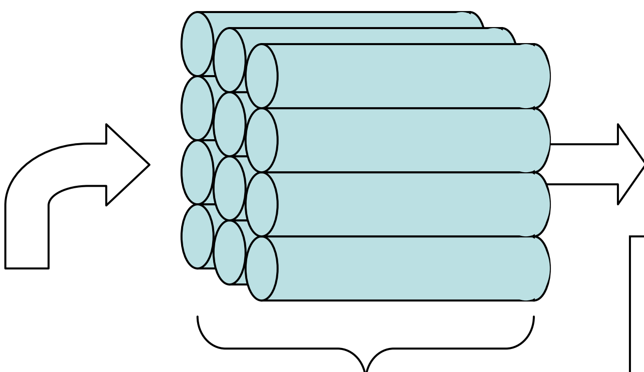
Flow-Through Bio-Reactor Design

Membrane Biofilm Reactor

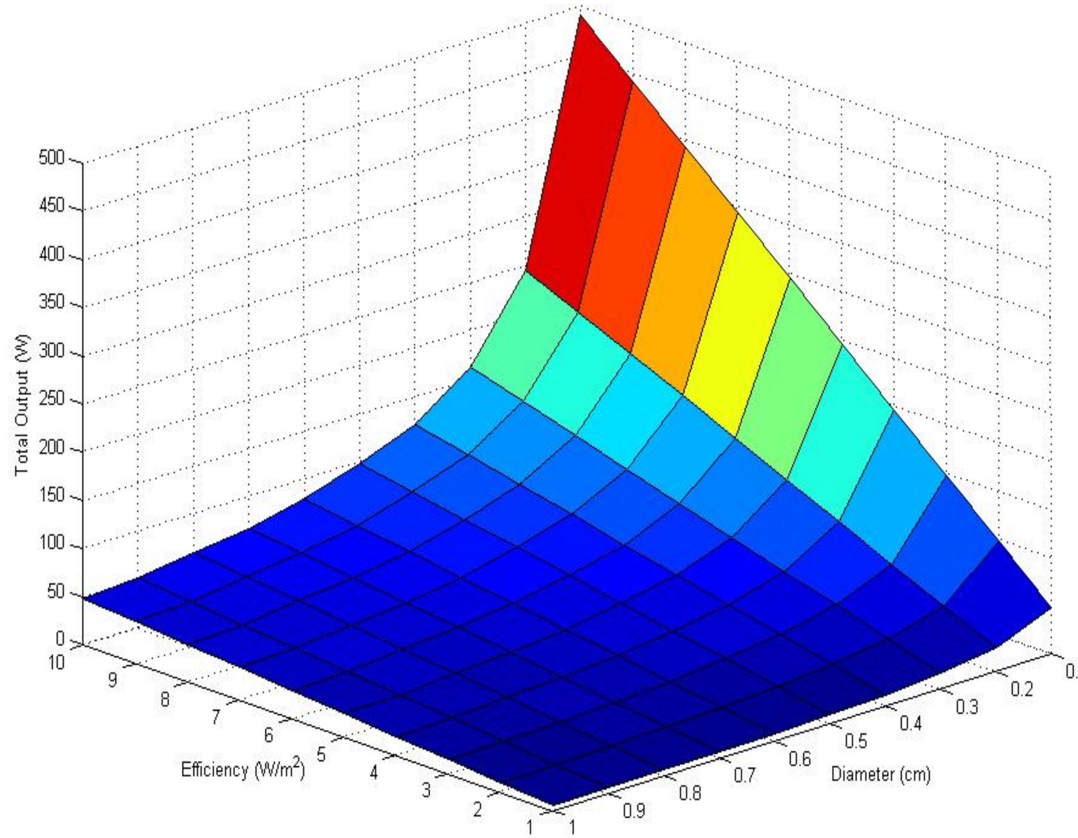
Courtesy: Rittman, 2004



Membrane Biofilm Reactor



Tubular Flow-Through



Power Output 1ftx1ft Flow-Through MFC with parallel tubular Rod

- Sizing Model For Flow Through
- Example Result: At 5 W/m^2, 0.5 cm tube → **1kw ~ 1/3 m^3**

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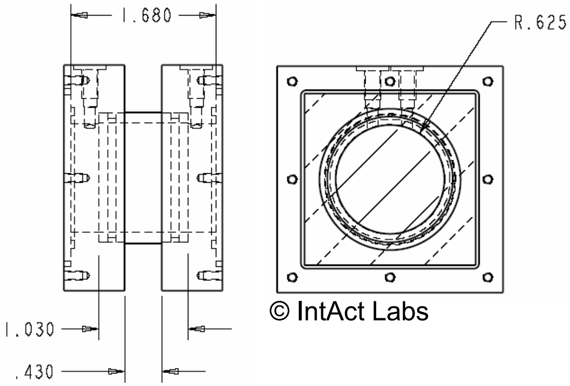
Experiment 1: Microbial Fuel Cell Anode Optimization

- **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. sulferreducens
  - 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. sullf. Cultured, Anodes Fabricated



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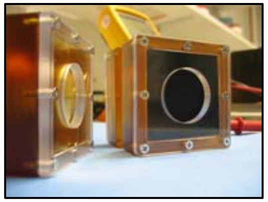

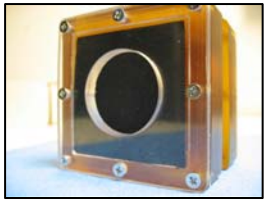

MFC at IntAct

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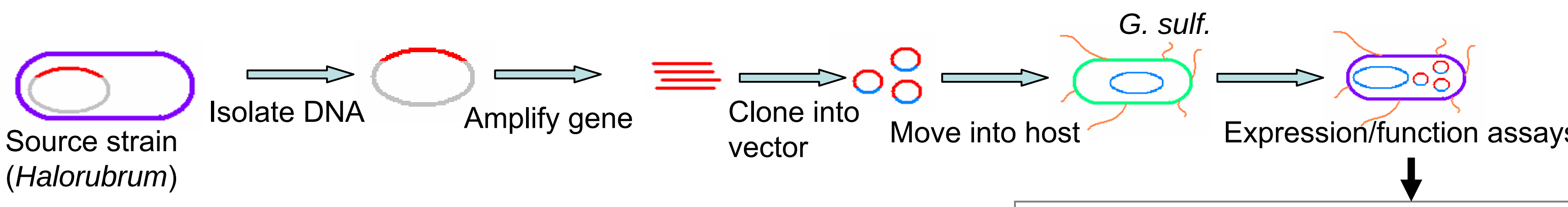
Experiment 2: Expression of Rhodopsin in Geobacter

- **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



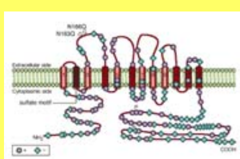
1. spectrophotometer (membrane absorption)
2. Protein expression (Western blot)
3. Microbial Photo-reaction (Microbial Fuel Cell)

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

Presentation Outline

Create Database → Select example applications → Bio-Electric Chamber Conceptual Design, Experiments / **Power Skin Conceptual Design Experiments** → Phase II Detailed Prototypes System Architectures

1. Create Database
2. Select example applications
3. Bio-Electric Chamber — Conceptual Design, Experiments
   Power Skin — Conceptual Design Experiments
4. Phase II — Detailed Prototypes System Architectures

 → Piezo-Electric Skin

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

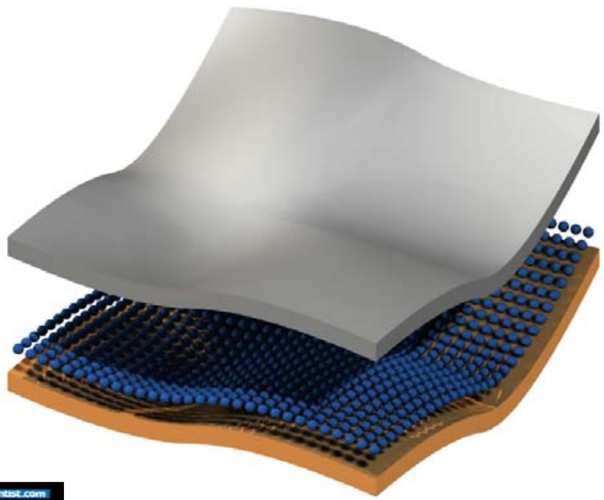
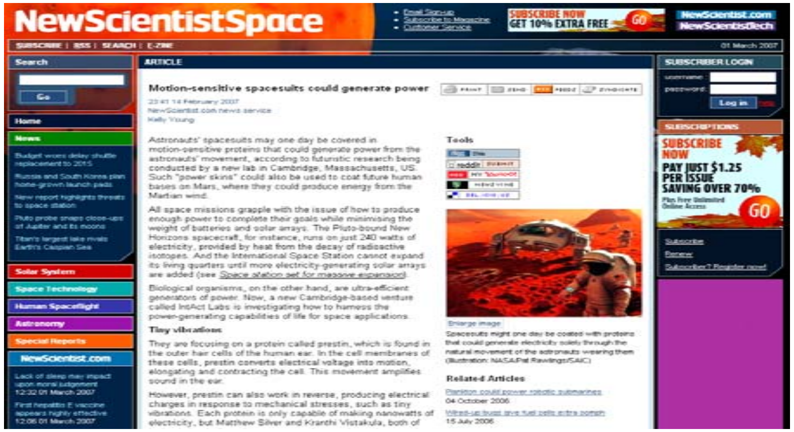


Image: Chris Lund © IntAct Labs



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ARTICLE

Motion-sensitive spacesuits could generate power

23:41 14 February 2007

NewScientist.com news service

Kelly Young

Astronauts' spacesuits may one day be covered in motion-sensitive proteins that could generate power from the astronauts' movement, according to futuristic research being conducted by a new lab in Cambridge, Massachusetts, US. Such "power skins" could also be used to coat future human bases on Mars, where they could produce energy from the Martian wind.

All space missions grapple with the issue of how to produce enough power to complete their goals while minimising the weight of batteries and solar arrays. The Pluto-bound New Horizons spacecraft, for instance, runs on just 240 watts of electricity, provided by heat from the decay of radioactive isotopes. And the International Space Station cannot expand its living quarters until more electricity-generating solar arrays are added (see Space station set for massive expansion).

Biological organisms, on the other hand, are ultra-efficient generators of power. Now, a new Cambridge-based venture called IntAct Labs is investigating how to harness the power-generating capabilities of life for space applications.

Tiny vibrations

They are focusing on a protein called prestin, which is found in the outer hair cells of the human ear. In the cell membranes of these cells, prestin converts electrical voltage into motion, elongating and contracting the cell. This movement amplifies sound in the ear.

However, prestin can also work in reverse, producing electrical charges in response to mechanical stresses, such as tiny vibrations. Each protein is only capable of making nanowatts of electricity, but Matthew Silver and Kranthi Vistakula, both of

Tools

Enlarge image

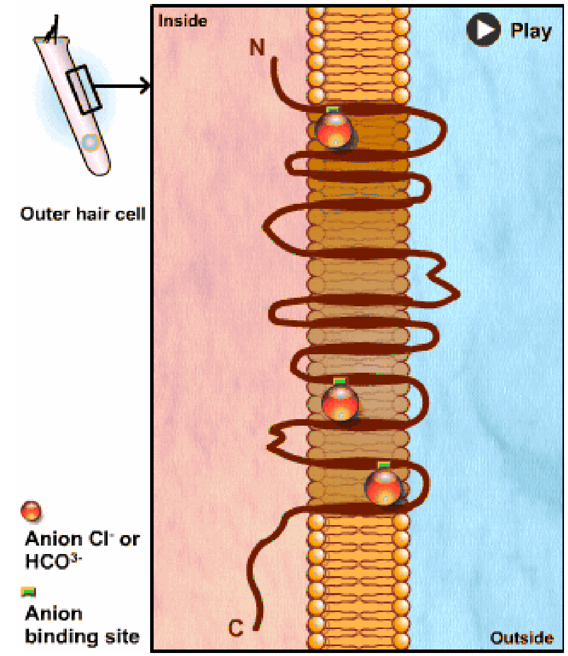
Spacesuits might one day be coated with proteins that could generate electricity solely through the natural movement of the astronauts wearing them (Illustration: NASA/Pat Rawlings/SAIC)

Related Articles

04 October 2006

15 July 2006

Sources of Power



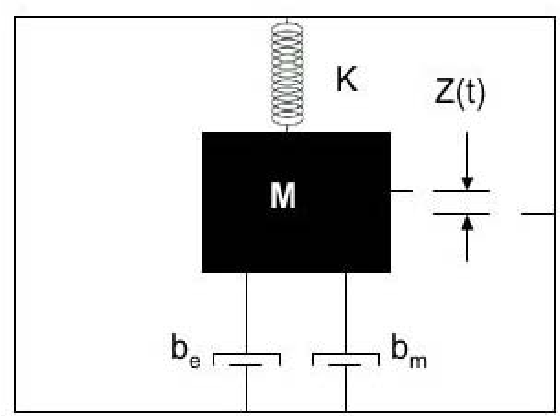
- **Martian Wind**
  - Pressure, Piezoelectric micro-turbines
  - Similar wind speeds to Earth, but lower density .022 kg/m^3

$$P = 1/2 * \rho * A * v^3$$

assume: 7m/s → 3 W/m^2

- **Mechanical or ambient structural vibrations**
  - Developing general model
  - Example: Vibrating Machinery
    - Observed vibrations at 120hz & acceleration of 2.25 m/s^2

$$P = \frac{m\varsigma_c \omega_n \omega^2(\omega/\omega_n^2)^3 Y^2}{(2\varsigma_T\, \omega/\ \omega_n)+(1-((\omega/\ \omega_n)^2)^2} = 0.1W$$

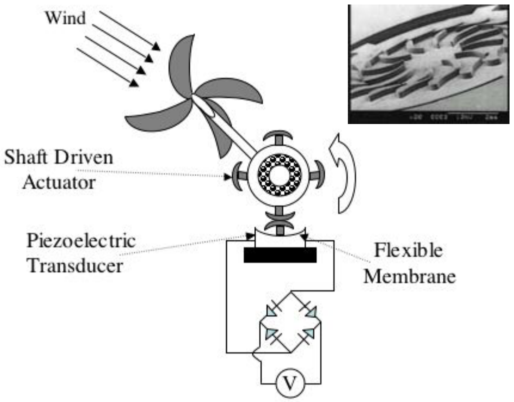


- **Electrical Potential**
  - 3 Chloride Ions Separated each Vibration

$$P = Ej*f = 1/2*C*V^2*f$$

Potential Applications

- Distributed Sensing
  - ~100 μW/node
  - Continuous Power Scavenging
  - “Throw-away” power source
- EVA
  - Surface area ~ .7 m^2
  - Power on the order **1 W**
  - Multiple Sensors without Wiring
- Large Scale Skin
  - Planned Mars structures/domes (d~30m) surface area ~3000 m^2
  - Power on the order **1 kW**

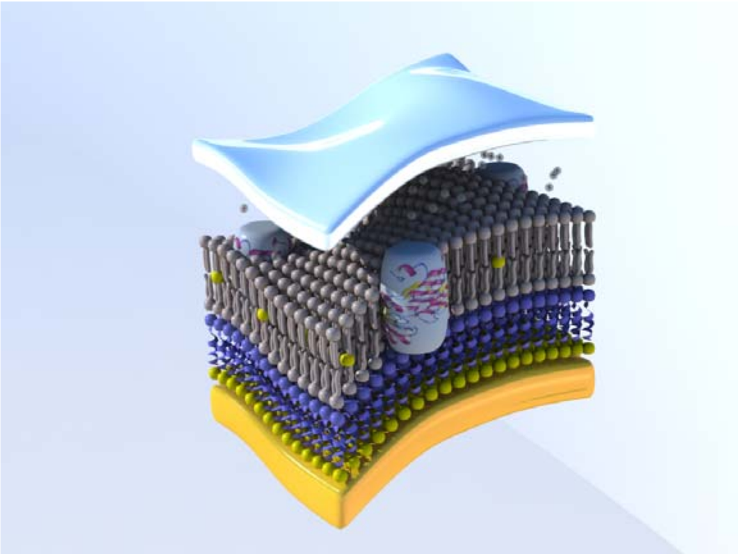



Covering Structures on mars

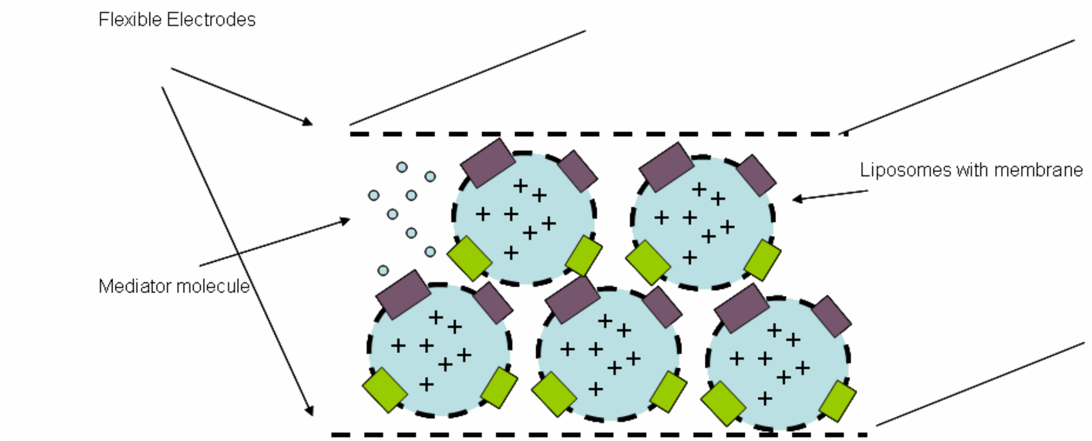

© IntAct Labs
Power for EVA Sensors

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-dox mechanisms
- **Optimization**
  - Increase Protein Output
  - Genetic engineering
  - Skin Robustness



Chris Lund © Intact Labs

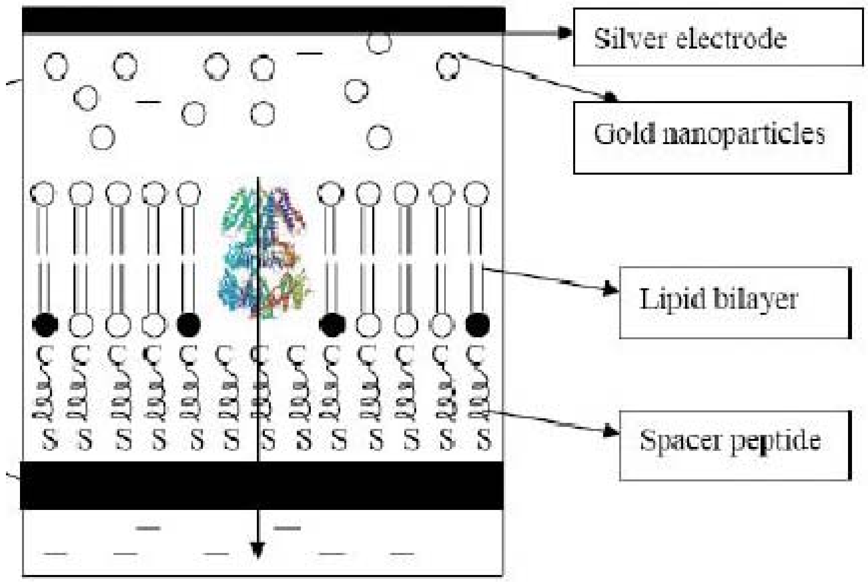


Liposomal Encapsulation

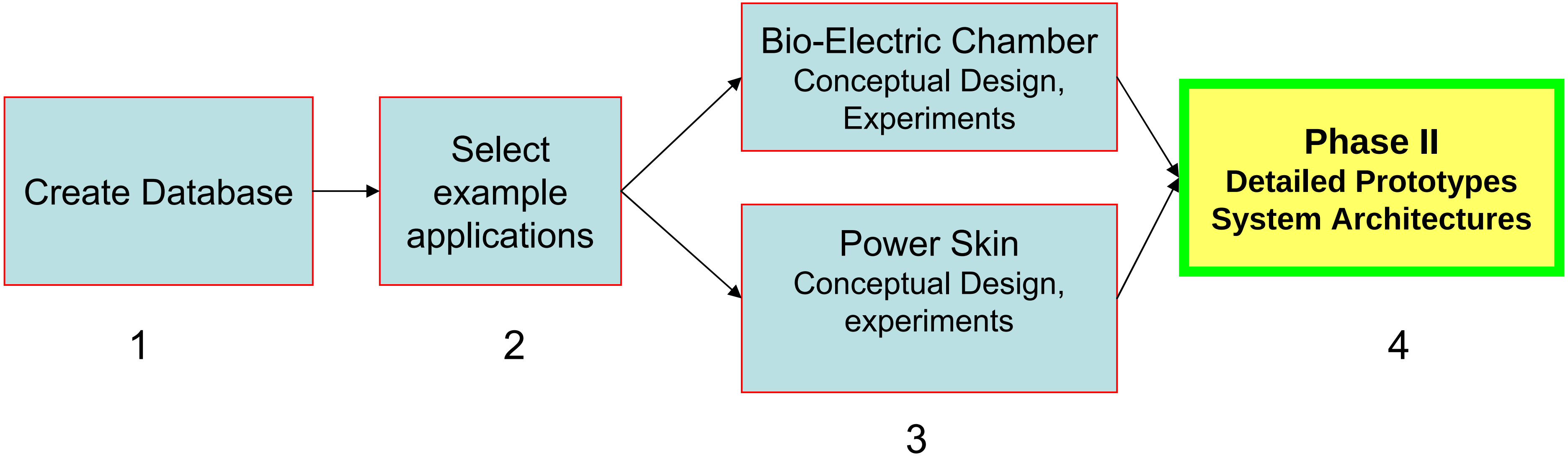
Cambridge, MA

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



Presentation Outline



Bio-Electric Power Architectures

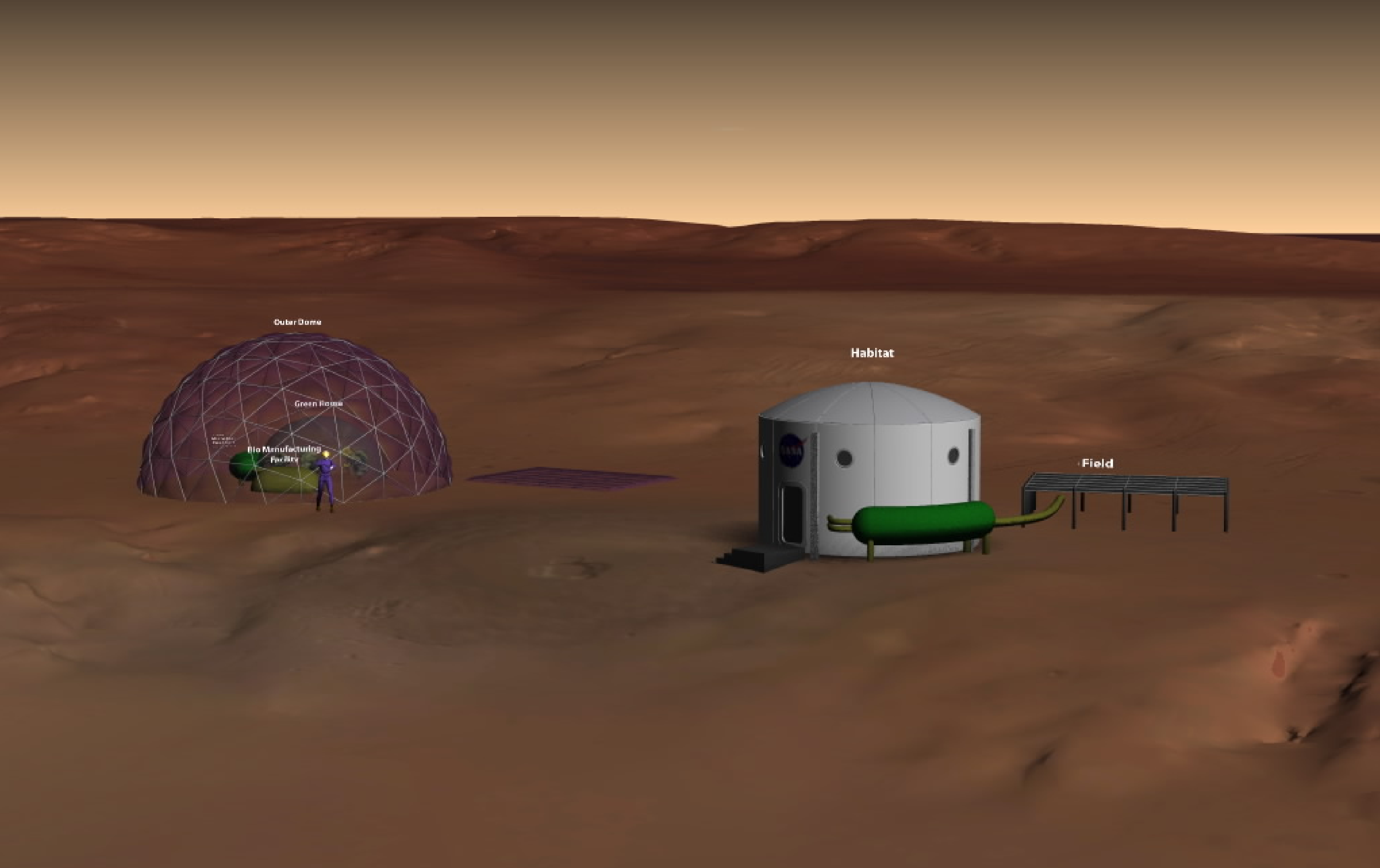
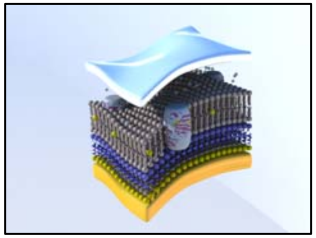


Image: Chris Lund

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

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?

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