Technology Solutions for Sustainable Energy

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Greening the Golden State, V 2.0
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Teaming and Funding

Funding Supports: NASA ASTEP, PIDDP, PPR and STTR, USRP, GSRP

DoD DARPA and DTRA

Nanomaterials for Devices Applications

Education and Engineering Research
Collaboration with academia and industrial partners

Multidisciplinary research areas focus

Composite Materials
- Combining inorganic and organic functionalities to form homogeneous hybrid composites
- Combining optoelectronic, electromechanical and electrochemical properties from single constituents
- Radiation shielding and protection (US patent)

Multifunctional Energy Generation and Storage Devices (all US patented technology)
- Fiber solar cell
- Wind energy harvester
- High energy density storage system
- Solar powered CO_2 conversion

Ultra Sensitive Spectroscopy and Imaging Techniques
- SERS and resonant Raman detections
- Chemical imaging, laser trapping

3D Photocatalytic Air Processor for Dramatic Reduction of Life Support Mass and Complexity

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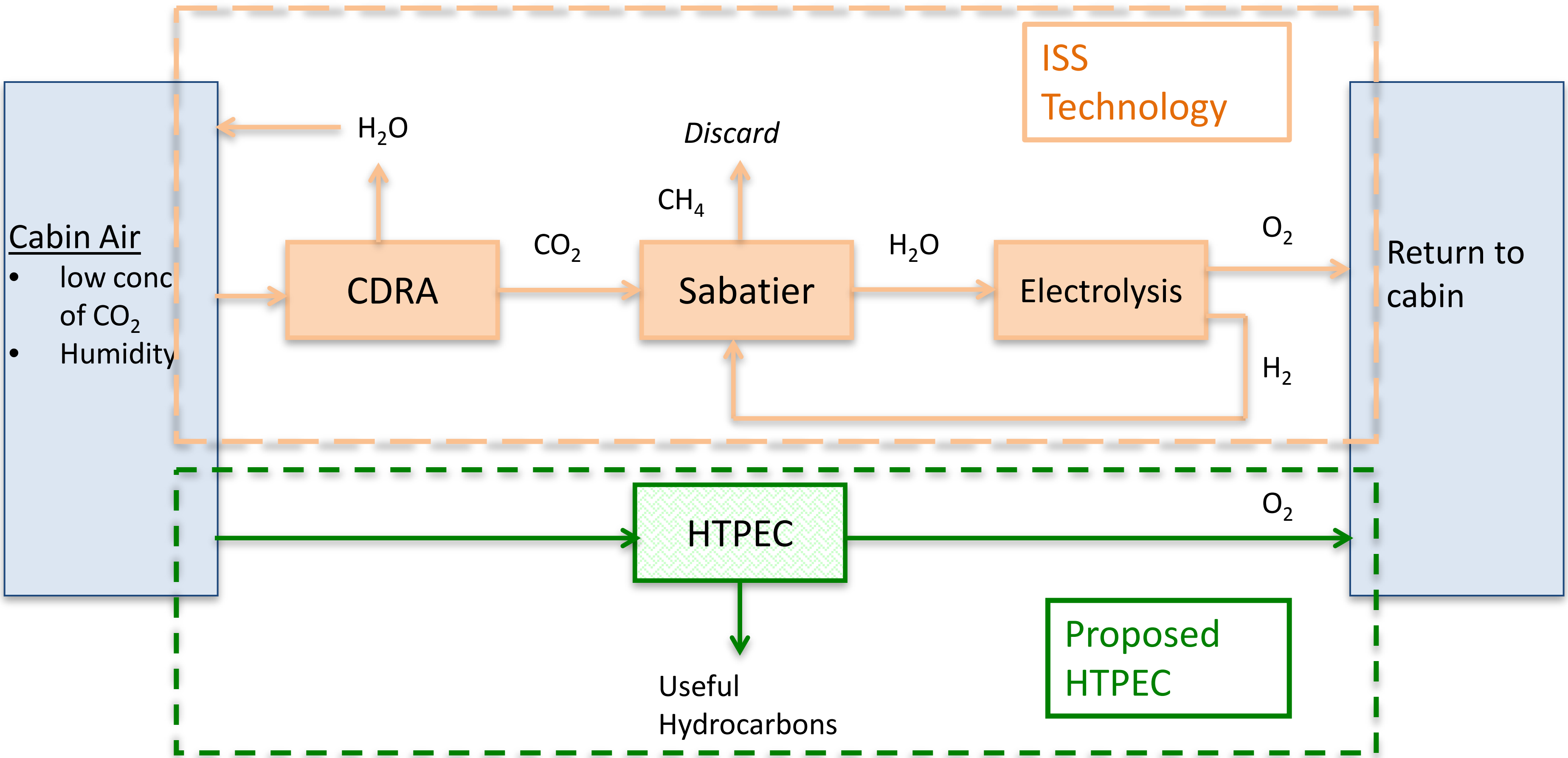
University of California, Los Angeles

Darrell Jan, John Hogan, Harry Jones, Kenny Cheung
NASA Ames Research Center, Moffett Field, CA

Bob Street
Palo Alto Research Center (PARC), Palo Alto, CA

Greg Whitting
Google X, Mountain View, CA

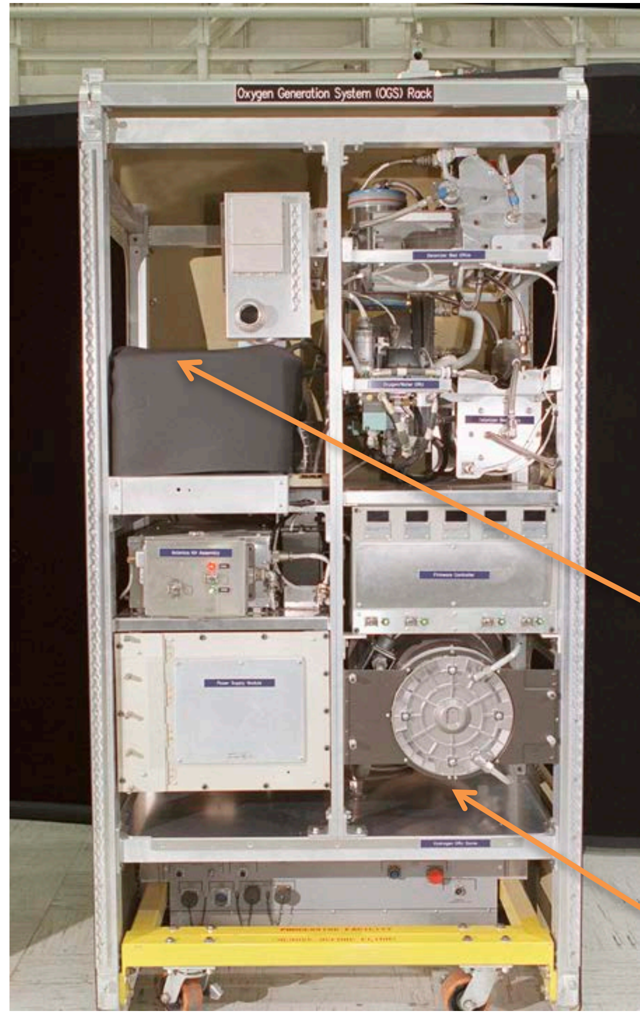
ISS management system and proposed alternative HTPEC system



HTPEC: high Tortuosity photoelectrochemical cell

Air Recovery Rack

Oxygen Generation System Rack



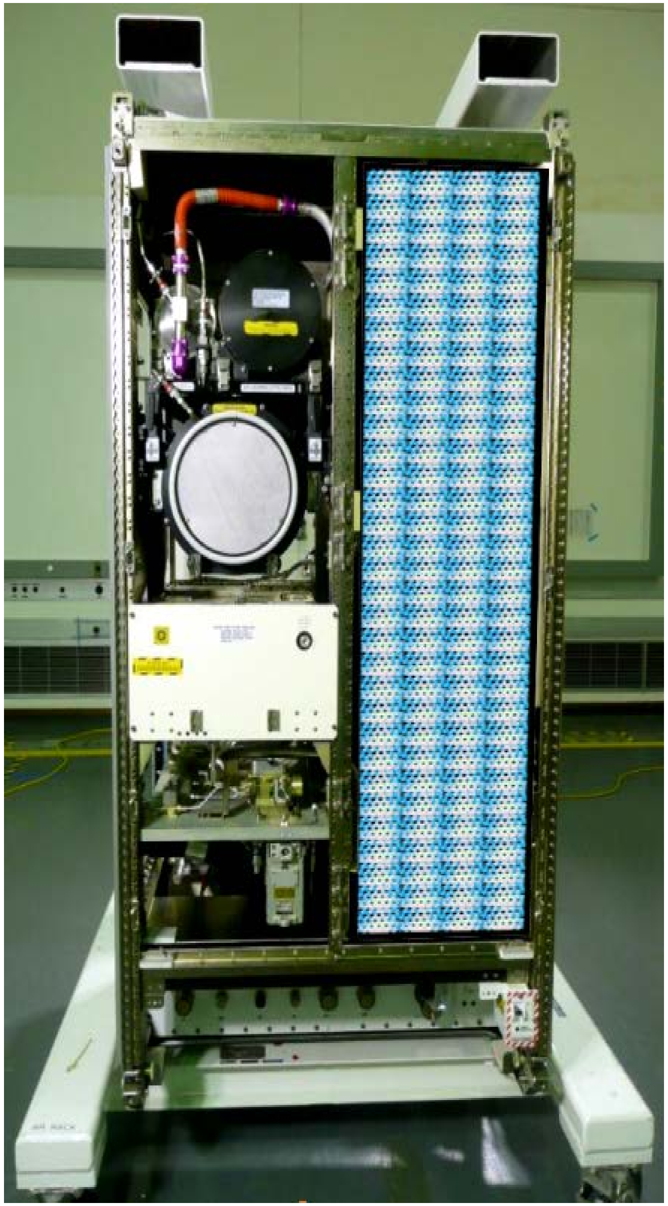
CO2 reduction
(Sabatier)

Electrolysis
Cell Stack

Carbon Dioxide
Removal Assembly
(CDRA)

Flexible packing geometry

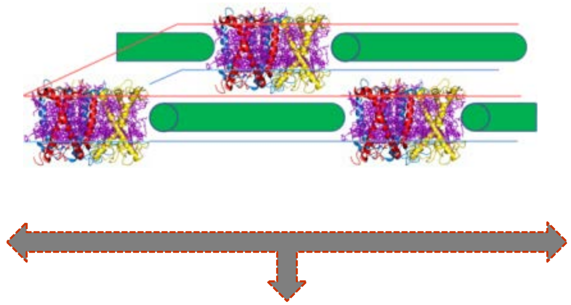
Sole energy from light

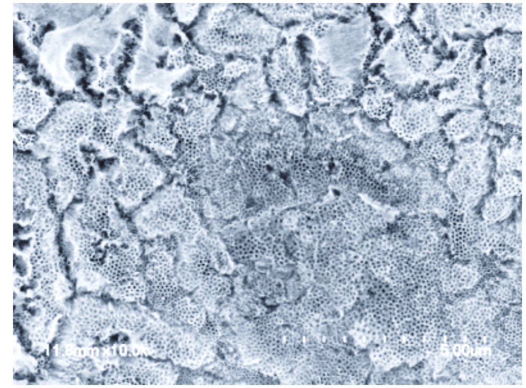


Artificial photosynthesis through inorganic photoelectrochemistry

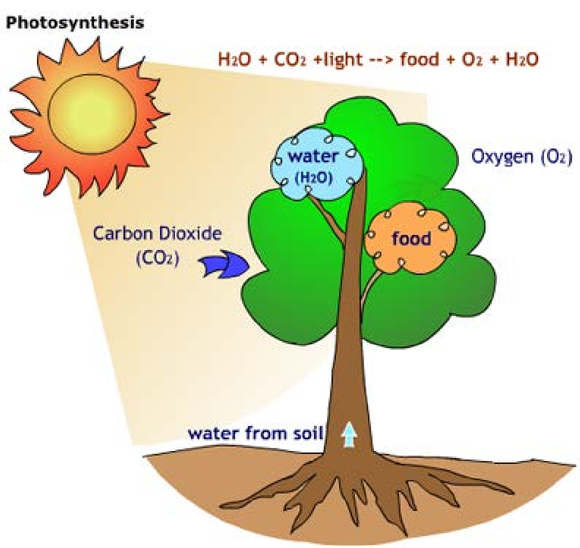
Red and blue light absorption:
natural leaves

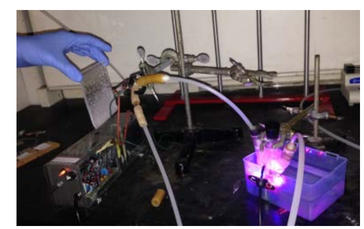
UV and green light absorption:
Artificial leaves of TiO_2 composites

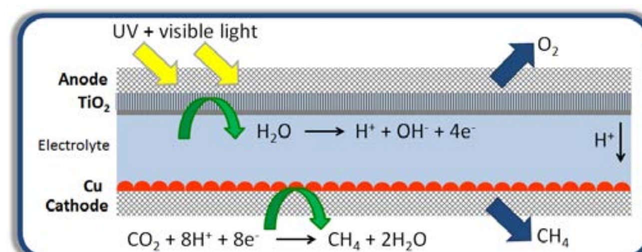




Broad solar energy absorption for life support and energy production in space

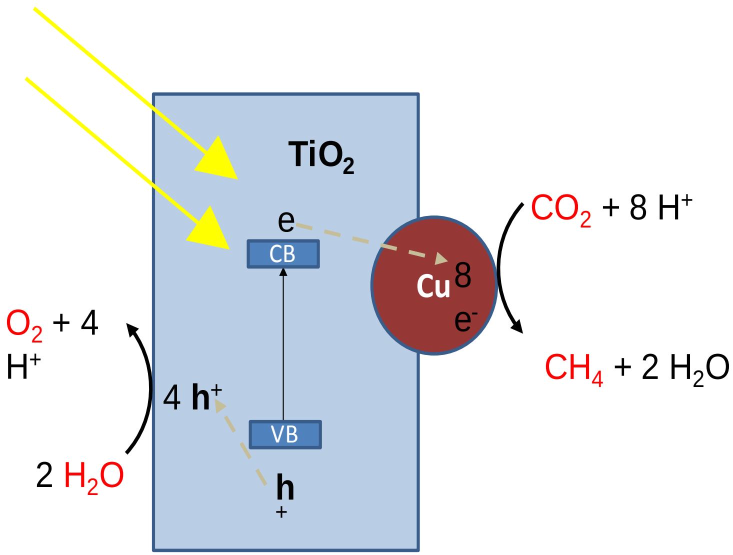






Cu/TiO_2 Composite Catalysts for "2-in-1 Photoelectrochemical Device":

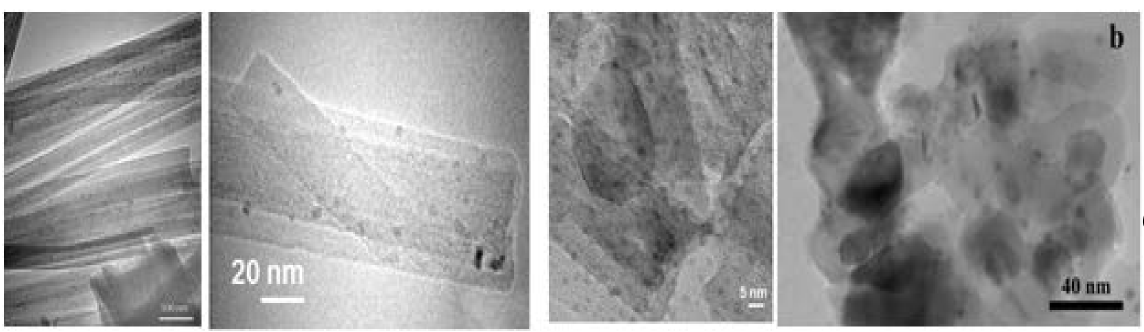
Photochemistry + Electrochemistry Coupled



$CO_2 + 2H_2O + hv$ (light) + ~~electricity~~ $\rightarrow CH_4 + 2O_2$

- All light powered
- No external electrical power
- Solid state device
- Low form factor thin-films

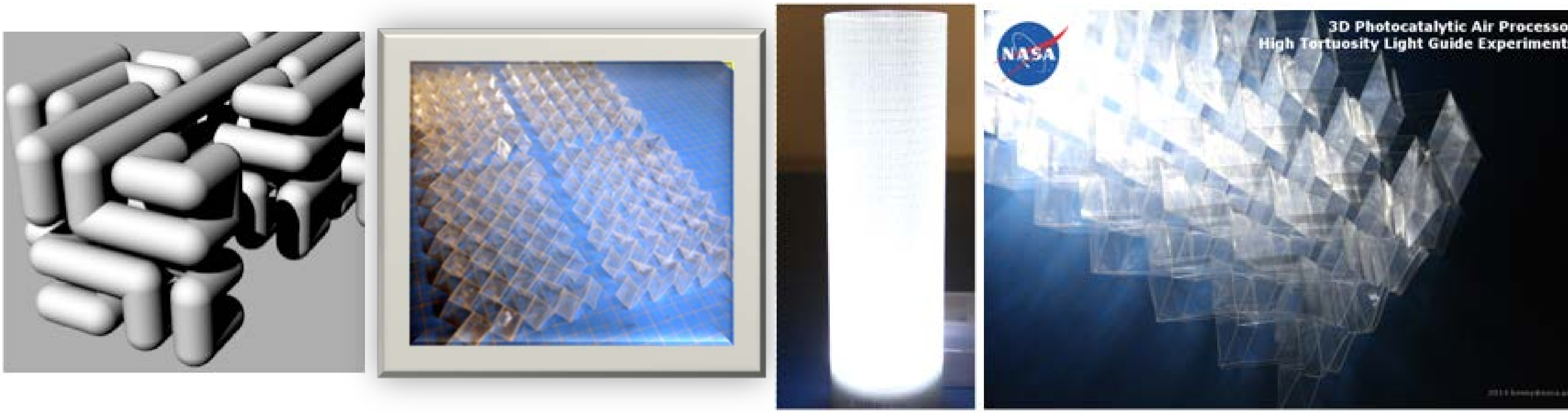
- 10x more efficient than similar devices
- Abundant materials
- Low cost solution-processing



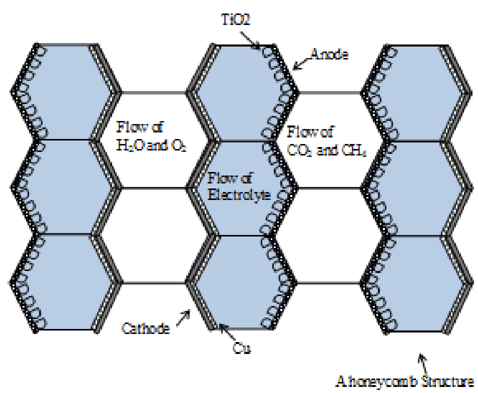
Chen, US patent* 9528192 B1 *2016

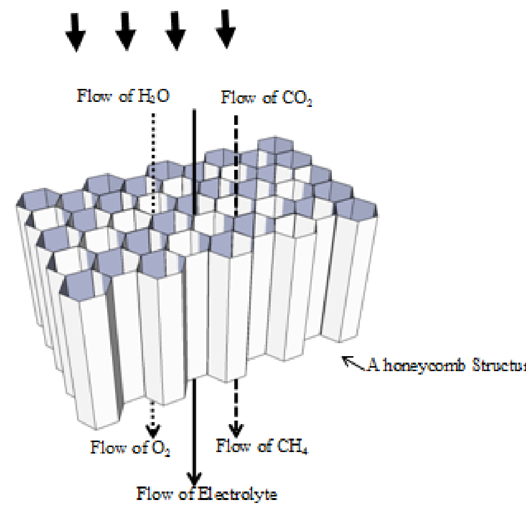
Micrographs (TEM) of TIO2 with Cu nanoparticle films

High efficiency mass transport & light transmission in a lightweight package



Space-filling high tortuosity tubular and efficient light pathway device designs





Honey comb device design as multifunctional structures

Current Artificial Photosynthesis Research

- NSF and DOE
  - Efficiency
  - Fundamental materials and devices
  - Energy generation and storage
- NASA
  - Power, mass, safety
  - ISRU
  - Life support
- DoD
  - Portable and *in situ* CO2 Conversion Devices

Our HTPEC has broad applications to all above

Current Artificial Photosynthesis Efforts

Liu et al, Science **03 Jun 2016: Vol. 352, Issue 6290, pp. 1210-1213**

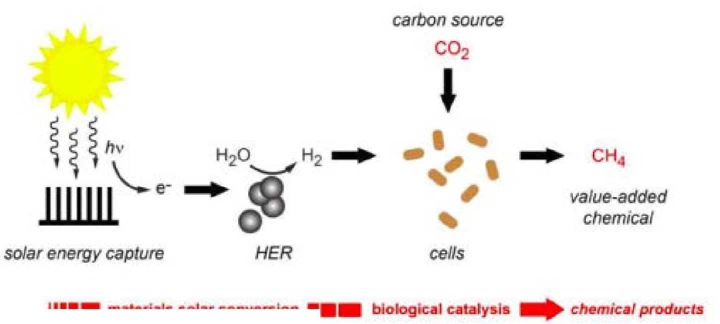
- Combined the hydrogen-oxidizing bacterium *Ralstonia eutropha* with a cobalt-phosphorus water-splitting catalyst
- Coupling this hybrid device to existing photovoltaic systems
- Claimed ~ 10% efficiency

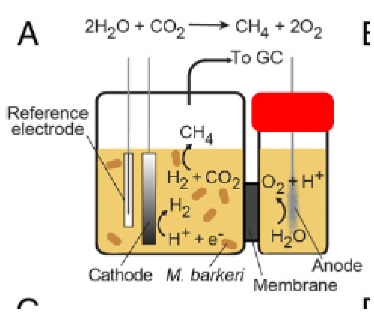
•Electrochemical cell
•PV electricity
•Co2P3/electrode

Nichols et al, PNAS, vol. 112 no. 3711461–11466 2015), doi: 10.1073/pnas.1508075112

•Inorganic and biological components coupled to transform light, water, and carbon dioxide to the value-added product methane.

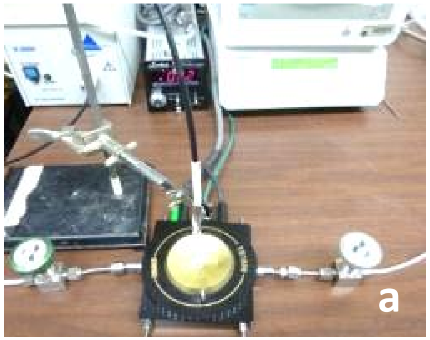
•Under simulated sunlight, with an energy-conversion efficiency of up to 0.38%.
Liu et al, Nano lett, 2015 15(5) pp 3634

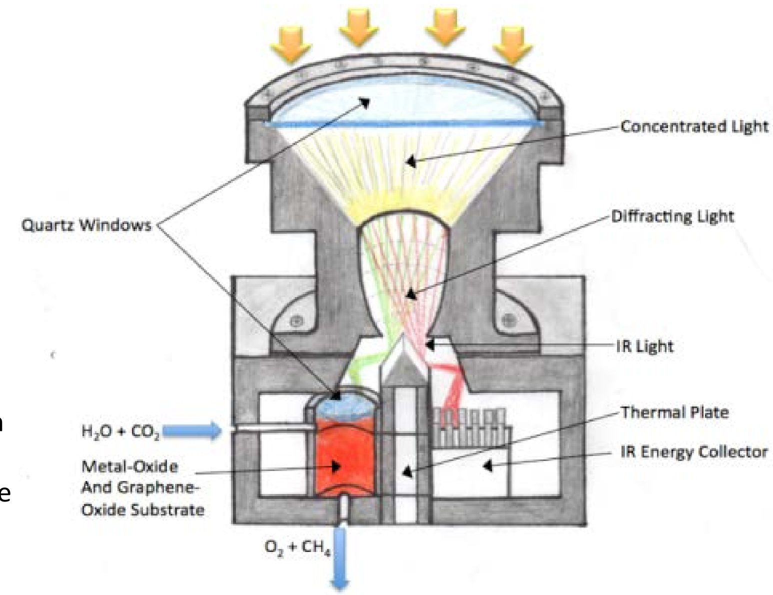


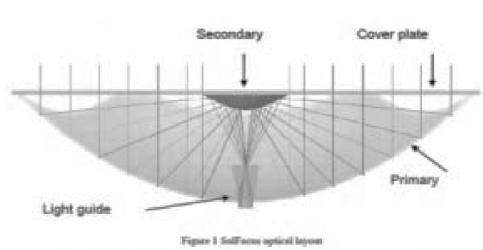


•Electrochemical cell
•PV electricity
•TiO2/InP electrodes

Evolution of Air Processor Device Platforms



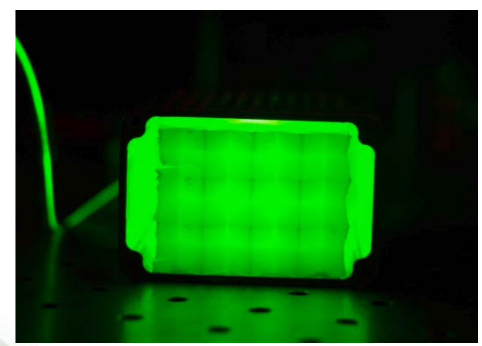




Liquid light concentrator coupled with optical fiber to transmit UV-Vis and IR light for PEC reaction and temperature control

Chen, B., "Optimum Solar Conversion Cell Configurations" US Patent, US 9033525 B1

MRS Bulletin Highlight s, Rice et al, (2011). Also see MRS Proceedings, 1325 , mrss11-1325-e05-06



US Patent 9528192 B1, 12/2016

HTPEC Research Evolution

- Fundamental Concept
  - Patented Catalysts
    - UC funding, CIF, STTR
  - Artificial Photosynthesis Enabled with Materials Science
    - CIF, NIAC (I&II)

- Technology Implementation Strategy (*Lab Scale to Mission*)
  - Tortuous pathway
  - 3D printing device concept

- Systems Analysis and Design
  - Mission Scenario and constraints

Nanomaterials Enabled Thin Film Devices

Scalable Materials Development

- Metal oxide nanowires
  - TiO_2
  - MnO_2
  - Co_3O_4
  - V_2O_5
- Carbonaceous materials
  - Reduced graphene oxides
  - CNT composites
- Metallic nanostructures
  - Ag nanowire arrays
  - Cu nanoparticles

Low Cost Devices Fabrications

- Composite nanostructures
  - Interfacial interaction
  - Morphology and alignment
- Electron mobility
  - Charge transfer
  - Electron transport
- Thin film processes
  - Langmuir Blodgett processes
  - Electrophoretic deposition
  - Self-assembly

Potential collaboration opening (2017)

CO_2 photoelectrochemical conversion

- photocatalyst and electrocatalyst composite

Applications:

- NASA life support and *in situ resource utilization*
- solar fuel production and carbon sequestration

Supercapacitor for high energy and power density

- multilayer composite fabrication

Applications:

- NASA energy storage at the extreme environment
- Off grid, EV energy storage

Raman imaging and surface enhanced Raman scattering (SERS)

- dense metallic nanowire array thin film substrates

Applications:

- NASA planetary instrument and astrobiology for life detections
- ultra sensitive detection and imaging for food and national secerity