Tandem particle-slurry batch reactors for solar water splitting

Shane Ardo

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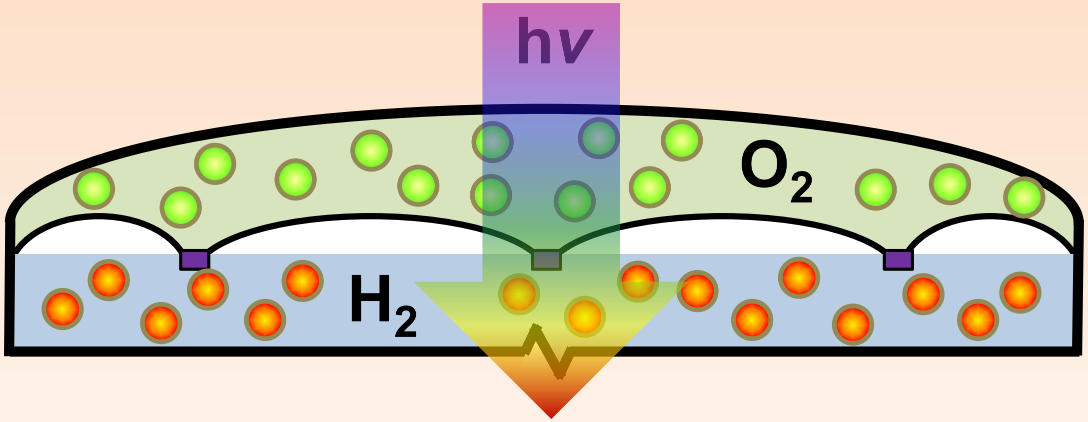


Overview

Project Timeline

- Start date: August 1, 2015
- New end date: January 31, 2018

  (30-month period of performance)

Project Budget

• Total budget:	$1,248,063
– Federal funds:	$ 993,759
– UCI cost share:	$ 254,304

• Funding by year (UCI only)	
– Year 1 spent:	$ 410,258
– Year 1 budget:	$ 412,943
– Year 2 spent*:	$ 93,400
– Year 2 budget:	$ 300,901

* as of 3/31/2017

Barriers Addressed

- (AG) Integrated Device Configurations
- (AH) Reactor Designs
- (AI) Auxiliary Materials
- (AJ) Synthesis and Manufacturing

Partners / Collaborators

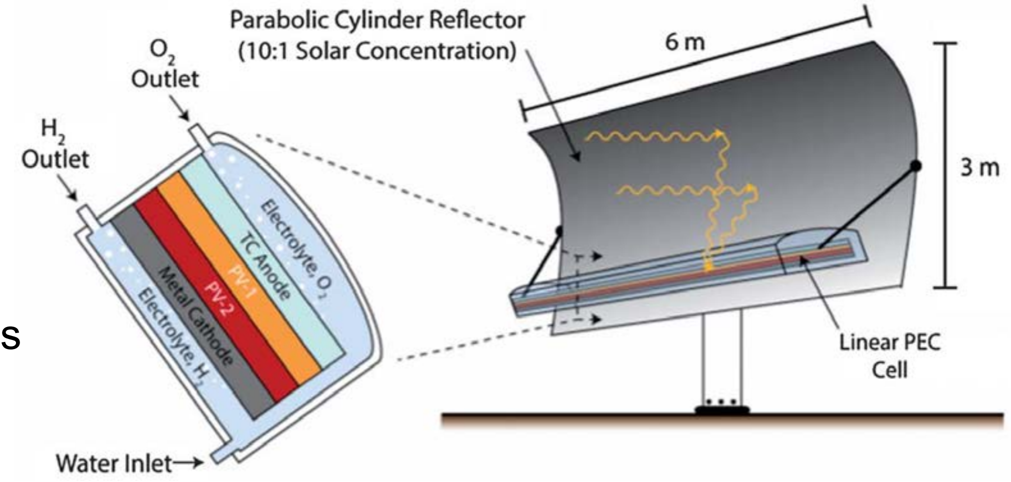
- Device-physics modeling and simulation contributors
  - **Lawrence Berkeley National Laboratory & JCAP** (Adam Weber, *sub-recipient*)
  - **California Institute of Technology & JCAP** (Chengxiang Xiang, *sub-contracted advisor*)
- Materials contributors
  - **Tokyo University of Science** (Akihiko Kudo, *unfunded*)

Relevance: Motivation

Wafers (Type 4) and Particles (Type 2)

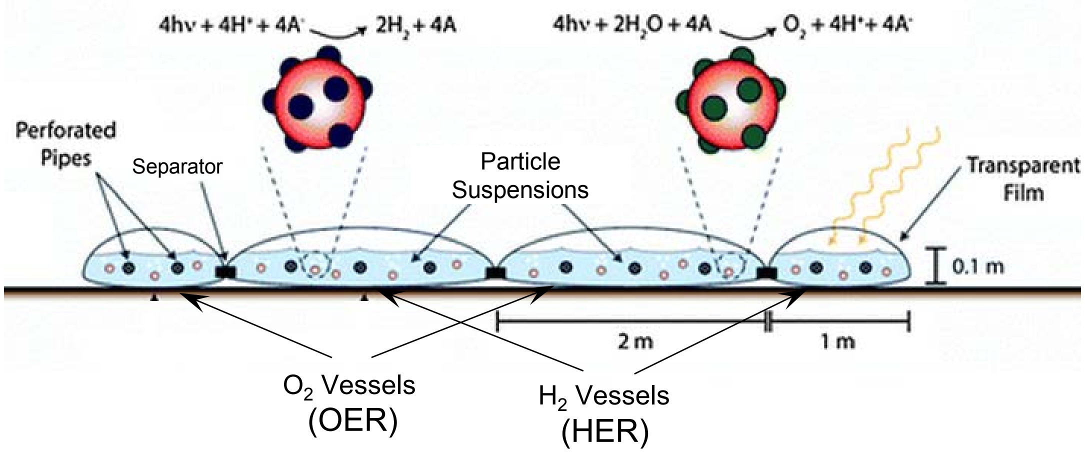
Fixed-electrode Design

- Wafers immersed in electrolyte
- Optical concentration of ≥ 10x
- Could meet MYRD&D targets
  - – High-efficiency materials
  - – Large reductions in materials costs

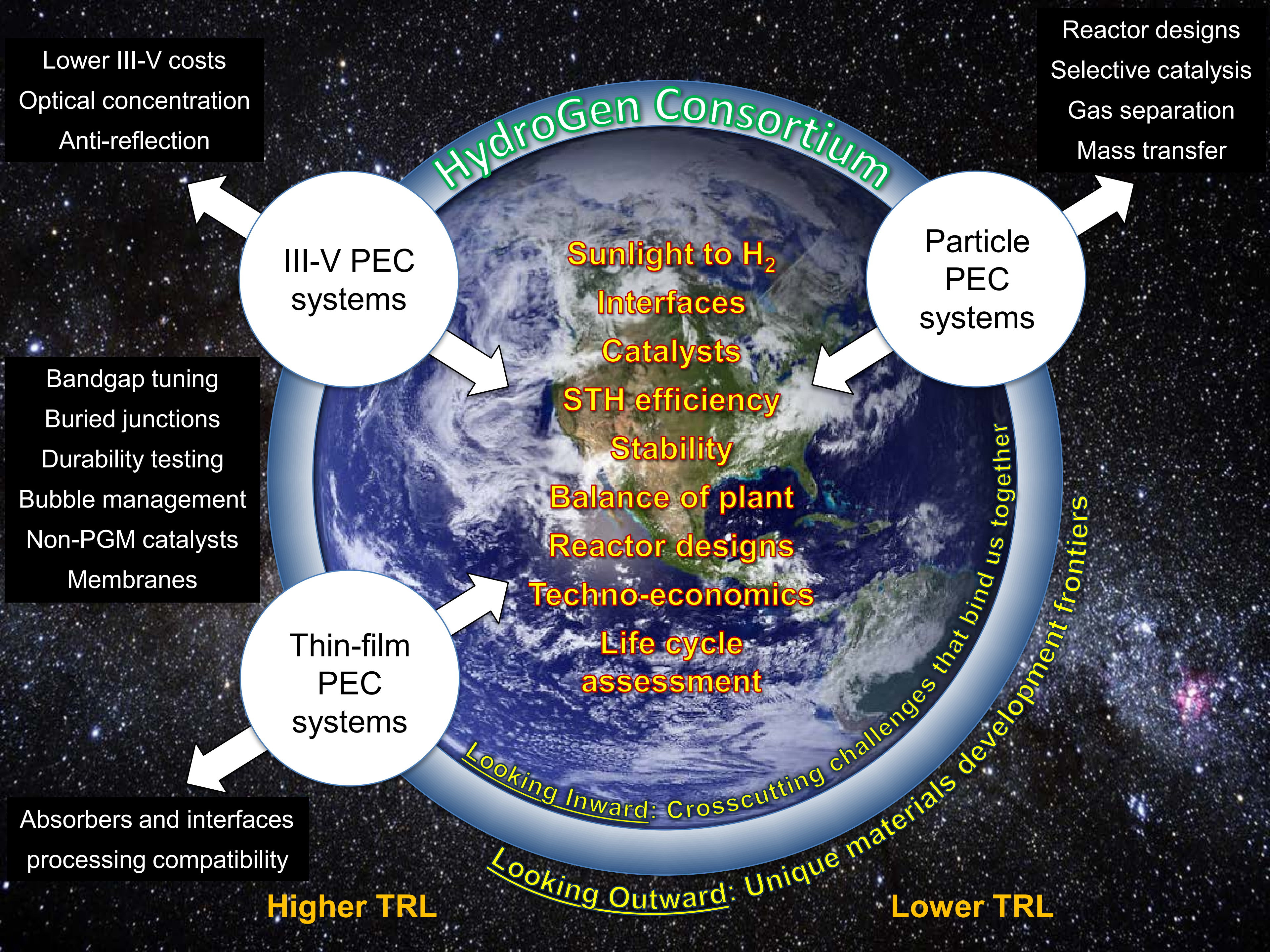


Particle-slurry Design

- Two particle suspensions
- Side-by-side plastic "baggies"
- Porous via allows mixing of the molecular redox shuttle (A/A$^-$)
- Requires many pumps & pipes
- Could meet MYRD&D targets
  - – Less stringent requirements
  - – TRL is very low



Directed Technologies, Inc., DOE Report, 2009 & Pinaud, …, Ardo, …, Jaramillo, *Energy Environ. Sci.*, 2013, *6*, 1983



HydroGen Consortium

Lower III-V costs
Optical concentration
Anti-reflection

III-V PEC systems

Bandgap tuning
Buried junctions
Durability testing
Bubble management
Non-PGM catalysts
Membranes

Particle PEC systems

Reactor designs
Selective catalysis
Gas separation
Mass transfer

Thin-film PEC systems

Absorbers and interfaces processing compatibility

Sunlight to H_2
Interfaces
Catalysts
STH efficiency
Stability
Balance of plant
Reactor designs
Techno-economics
Life cycle assessment

Looking Inward: Crosscutting challenges that bind us together

Looking Outward: Unique materials development frontiers

Higher TRL **Lower TRL**

Relevance: Concept

Project Objective: **Experimentally validate** a *new design* for scalable solar-H_2 technologies using laboratory-scale prototype particle suspension reactors

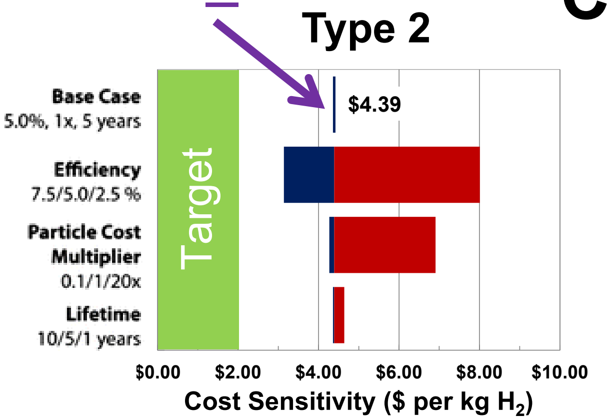
August 2016 Objective: **Numerically demonstrate** that the *new reactor design* can sustain a ≥ 1% solar-to-hydrogen (STH) conversion efficiency

	MYRD&D Targets for a Type 2 Reactor				
Characteristics	**2011**	**2015**	**Proposed**	**2020**	**Ultimate**
H_2 Cost ($/kg)	N/A	28.60	20.00	4.60	2.10
η_{STH} (%)	N/A	1.0	1.0	5.0	10

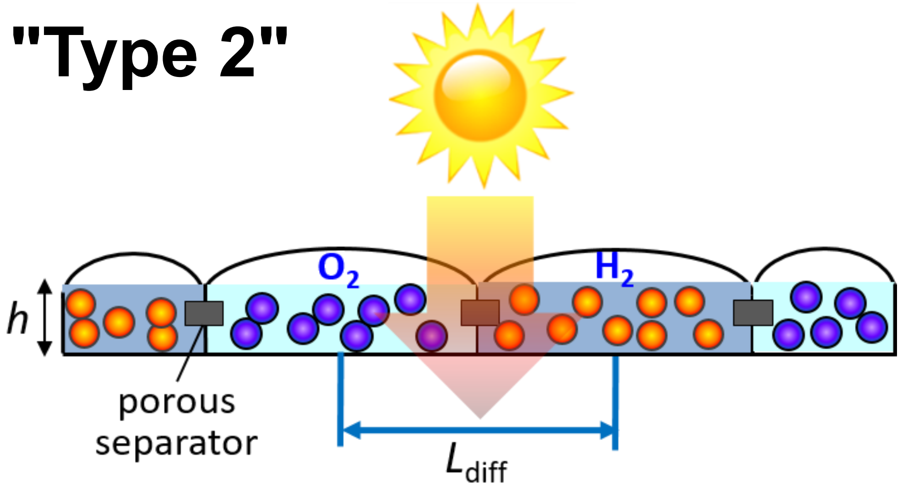
DOE Barriers	Project Goal
(AJ) Synthesis and Manufacturing **(AG) Integrated Device Configurations**	• Synthesize state-of-the-art light-absorber nanoparticle photocatalysts as powders, inks, and thin films • Electrodeposit electrocatalysts on light-absorber nanoparticle photocatalysts using solid-state chemistry, photo(electro)deposition, and bipolar electrochemistry
(AH) Reactor Designs	• Model physics and techno-economics of new tandem two-compartment particle suspension reactor designs • Fabricate model reactors with *in situ* monitoring capabilities, and assess redox shuttle transport rates
(AI) Auxiliary Materials	• Identify optimal redox shuttles based on optical transparency, rates of mass transport, and efficiency of selective electrocatalysis

Approach: Concept

$4.39 at 5%



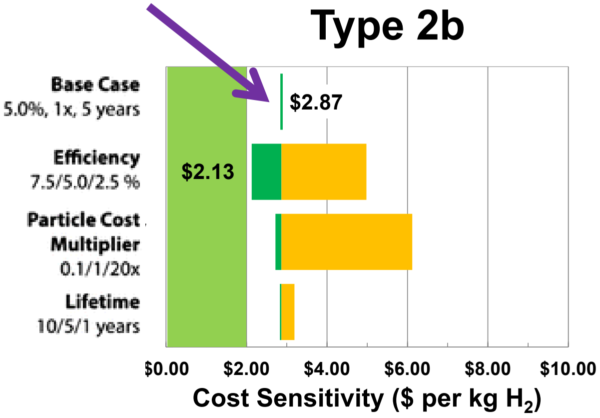
Current "Type 2"

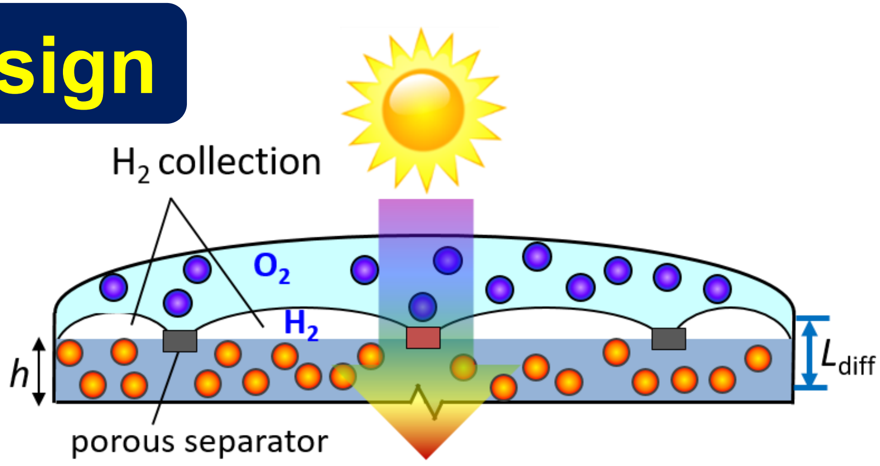


New Stacked-Reactor Design

("Type 2b")

$2.87 at 5%

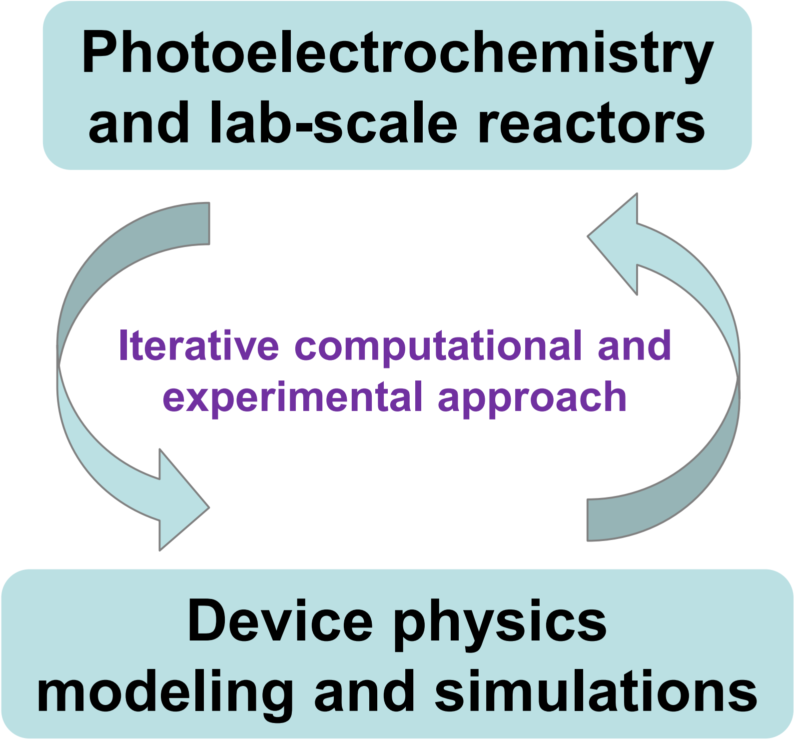




- Tandem efficiency advantage (not w/ SotA)
- > 10x smaller mass transport distances

Directed Technologies, Inc., DOE Report, 2009 & DOE H2A Analysis, https://www.hydrogen.energy.gov/h2a_production.html

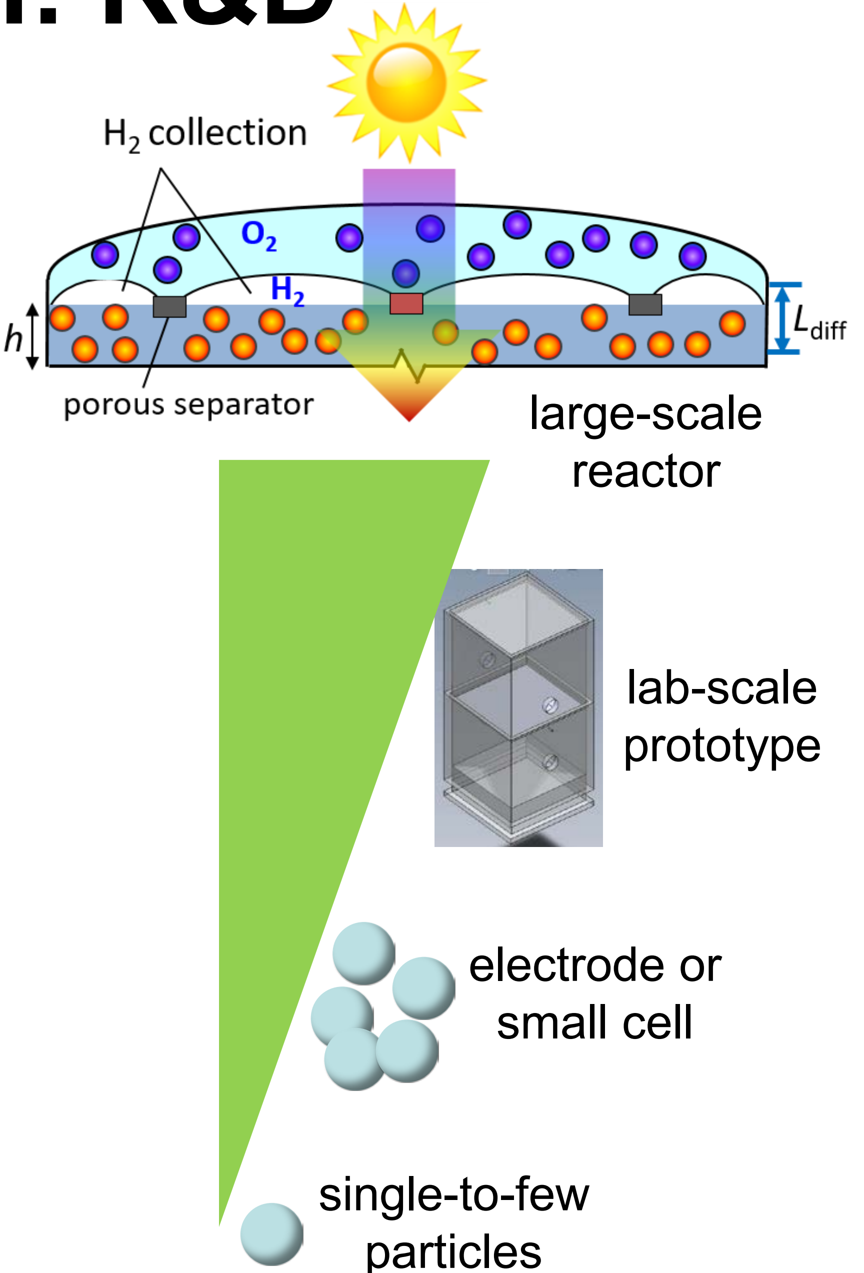
Approach: R&D



Photoelectrochemistry and lab-scale reactors

Iterative computational and experimental approach

Device physics modeling and simulations



large-scale reactor

lab-scale prototype

electrode or small cell

single-to-few particles

Approach: R&D Materials Choice

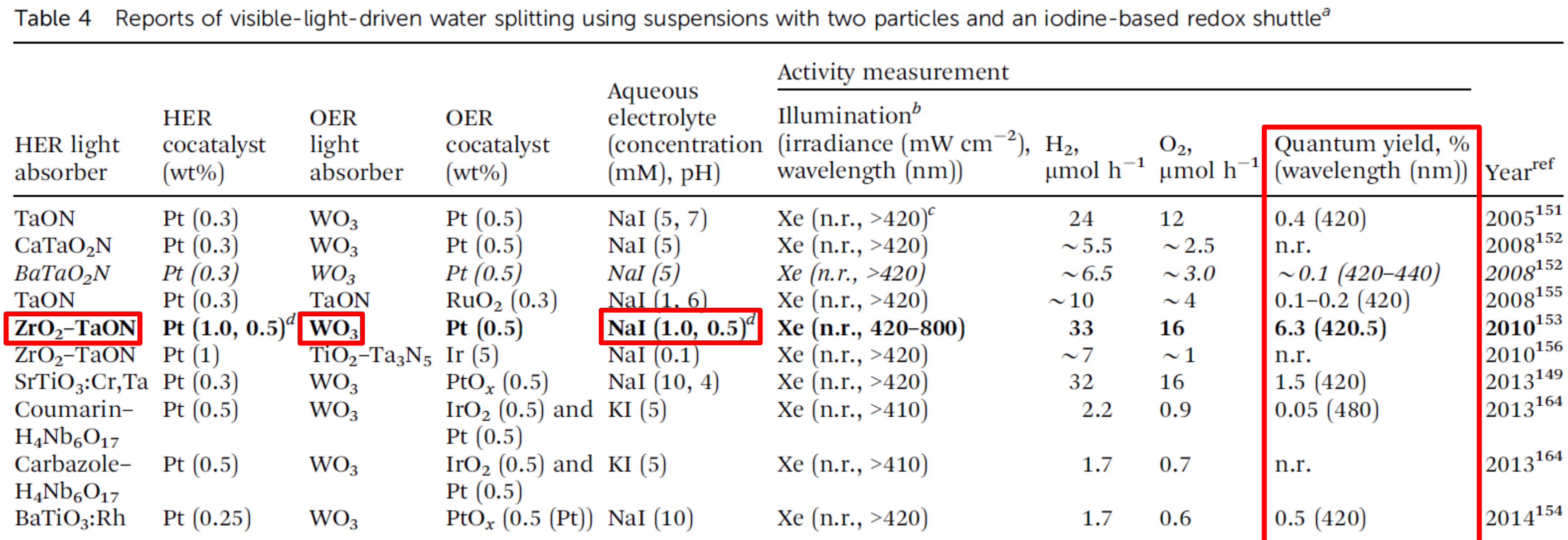


Table 4 Reports of visible-light-driven water splitting using suspensions with two particles and an iodine-based redox shuttle[a]

Domen

					Activity measurement				
HER light absorber	HER cocatalyst (wt%)	OER light absorber	OER cocatalyst (wt%)	Aqueous electrolyte (concentration (mM), pH)	Illumination[b] (irradiance (mW cm^{-2}), wavelength (nm))	H_2, μmol h^{-1}	O_2, μmol h^{-1}	Quantum yield, % (wavelength (nm))	Year[ref]
TaON	Pt (0.3)	WO_3	Pt (0.5)	NaI (5, 7)	Xe (n.r., >420)[c]	24	12	0.4 (420)	2005[151]
$CaTaO_2N$	Pt (0.3)	WO_3	Pt (0.5)	NaI (5)	Xe (n.r., >420)	~5.5	~2.5	n.r.	2008[152]
$BaTaO_2N$	*Pt (0.3)*	*WO_3*	*Pt (0.5)*	*NaI (5)*	*Xe (n.r., >420)*	*~6.5*	*~3.0*	*~0.1 (420–440)*	*2008*[152]
TaON	Pt (0.3)	TaON	RuO_2 (0.3)	NaI (1, 6)	Xe (n.r., >420)	~10	~4	0.1–0.2 (420)	2008[155]
ZrO_2–TaON	**Pt (1.0, 0.5)**[d]	**WO_3**	**Pt (0.5)**	**NaI (1.0, 0.5)**[d]	**Xe (n.r., 420–800)**	**33**	**16**	**6.3 (420.5)**	**2010**[153]
ZrO_2–TaON	Pt (1)	TiO_2–Ta_3N_5	Ir (5)	NaI (0.1)	Xe (n.r., >420)	~7	~1	n.r.	2010[156]
$SrTiO_3$:Cr,Ta	Pt (0.3)	WO_3	PtO_x (0.5)	NaI (10, 4)	Xe (n.r., >420)	32	16	1.5 (420)	2013[149]
Coumarin–$H_4Nb_6O_{17}$	Pt (0.5)	WO_3	IrO_2 (0.5) and Pt (0.5)	KI (5)	Xe (n.r., >410)	2.2	0.9	0.05 (480)	2013[164]
Carbazole–$H_4Nb_6O_{17}$	Pt (0.5)	WO_3	IrO_2 (0.5) and Pt (0.5)	KI (5)	Xe (n.r., >410)	1.7	0.7	n.r.	2013[164]
$BaTiO_3$:Rh	Pt (0.25)	WO_3	PtO_x (0.5 (Pt))	NaI (10)	Xe (n.r., >420)	1.7	0.6	0.5 (420)	2014[154]

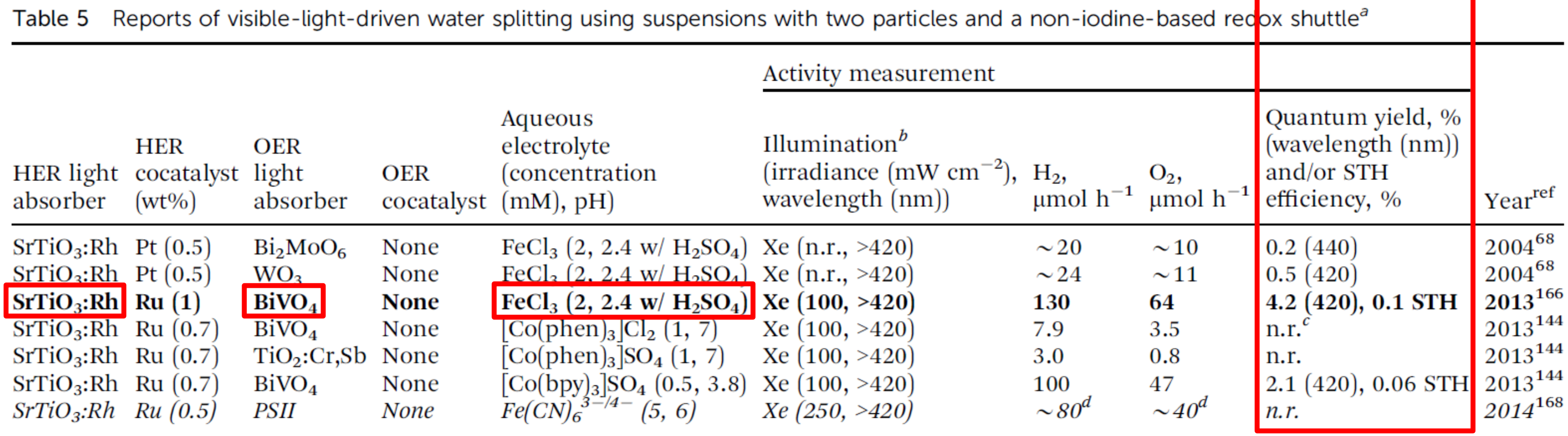


Table 5 Reports of visible-light-driven water splitting using suspensions with two particles and a non-iodine-based redox shuttle[a]

Kudo & Abe & Osterloh

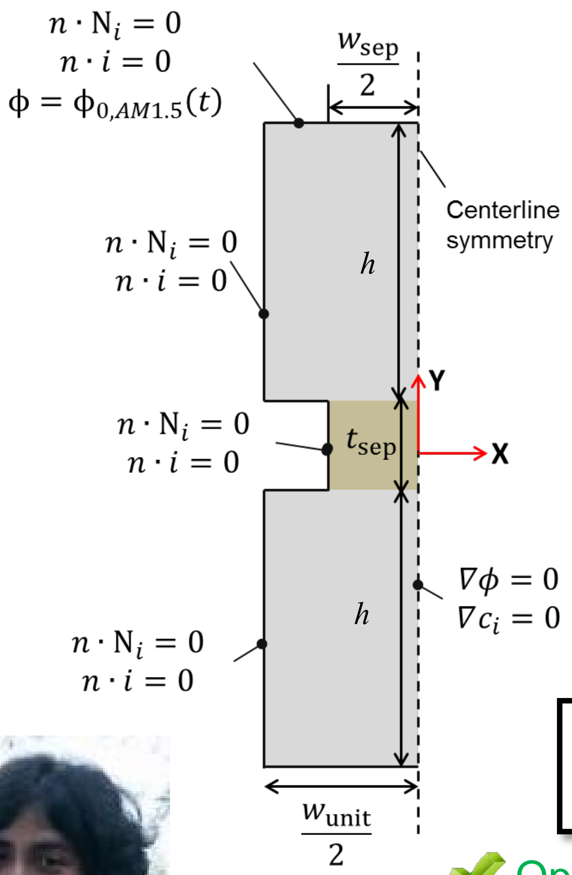
					Activity measurement				
HER light absorber	HER cocatalyst (wt%)	OER light absorber	OER cocatalyst	Aqueous electrolyte (concentration (mM), pH)	Illumination[b] (irradiance (mW cm^{-2}), wavelength (nm))	H_2, μmol h^{-1}	O_2, μmol h^{-1}	Quantum yield, % (wavelength (nm)) and/or STH efficiency, %	Year[ref]
$SrTiO_3$:Rh	Pt (0.5)	Bi_2MoO_6	None	$FeCl_3$ (2, 2.4 w/ H_2SO_4)	Xe (n.r., >420)	~20	~10	0.2 (440)	2004[68]
$SrTiO_3$:Rh	Pt (0.5)	WO_3	None	$FeCl_3$ (2, 2.4 w/ H_2SO_4)	Xe (n.r., >420)	~24	~11	0.5 (420)	2004[68]
$SrTiO_3$:Rh	**Ru (1)**	**$BiVO_4$**	**None**	**$FeCl_3$ (2, 2.4 w/ H_2SO_4)**	**Xe (100, >420)**	**130**	**64**	**4.2 (420), 0.1 STH**	**2013**[166]
$SrTiO_3$:Rh	Ru (0.7)	$BiVO_4$	None	$[Co(phen)_3]Cl_2$ (1, 7)	Xe (100, >420)	7.9	3.5	n.r.[c]	2013[144]
$SrTiO_3$:Rh	Ru (0.7)	TiO_2:Cr,Sb	None	$[Co(phen)_3]SO_4$ (1, 7)	Xe (100, >420)	3.0	0.8	n.r.	2013[144]
$SrTiO_3$:Rh	Ru (0.7)	$BiVO_4$	None	$[Co(bpy)_3]SO_4$ (0.5, 3.8)	Xe (100, >420)	100	47	2.1 (420), 0.06 STH	2013[144]
$SrTiO_3$:Rh	*Ru (0.5)*	*PSII*	*None*	*$Fe(CN)_6{}^{3-/4-}$ (5, 6)*	*Xe (250, >420)*	*~80*[d]	*~40*[d]	*n.r.*	*2014*[168]

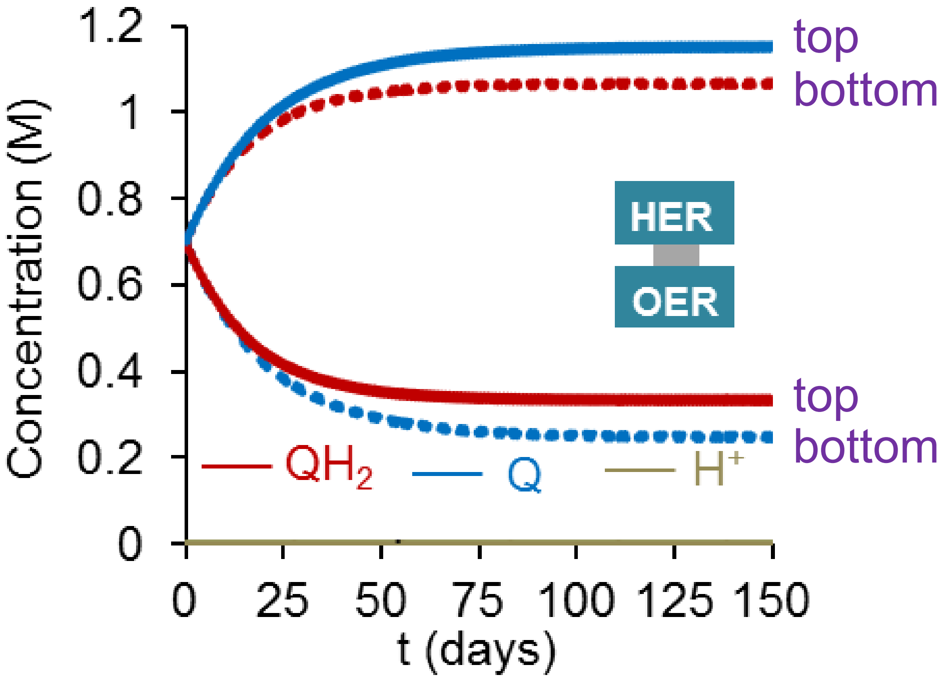
Fabian, Hu, Singh, Houle, Hisatomi, Domen, Osterloh & Ardo, *Energy Environ. Sci.*, 2015, *8*, 2825

Approach: Milestones

Description of Milestone	Due Date (Quarter)	Percentage Complete
Task 1.0 Numerical modeling and simulations of new reactor design		
M1.1.2 To the model, add advanced semiconductor charge transport, i.e. generation and recombination in the bulk and at surfaces. **(AH) – effective reverse saturation reaction rate implemented**	August 1, 2016 (**Q4**)	**100%**
D1.1.1 Go/No-Go Decision: Using 80% less pipes and 80% less pumping energy, verify 1% η_{STH}. **(AH, AI) – sustainable reactor demonstrated, with no required pumps or pipes**	August 1, 2016 (**Q4**)	**100%**
M1.1.3 To the model, add electromagnetic wave propagation, thermal effects, and multi-phase flow. **(AH, AI) – each of these physical processes has been implemented in part**	August 1, 2017 (**Q8**)	80%

Accomplishments: Go, with Q/QH$_2$



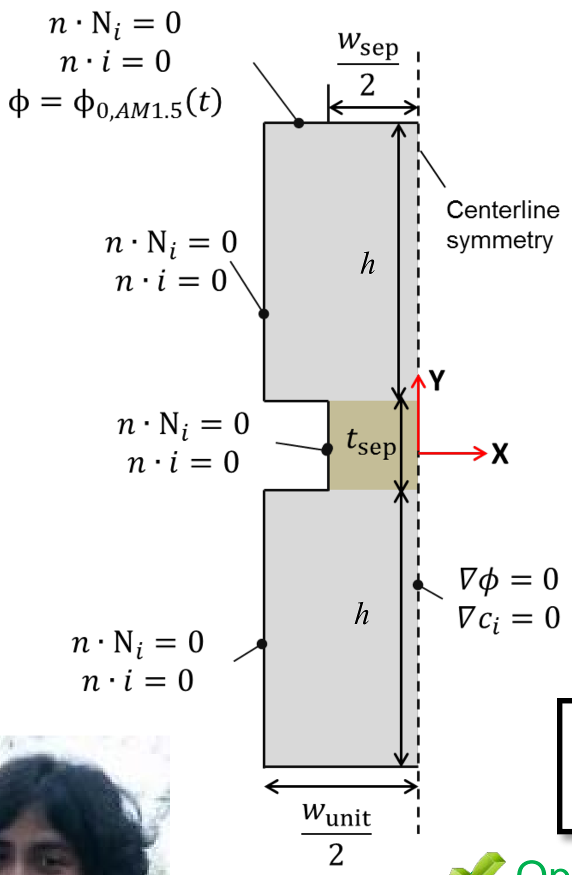


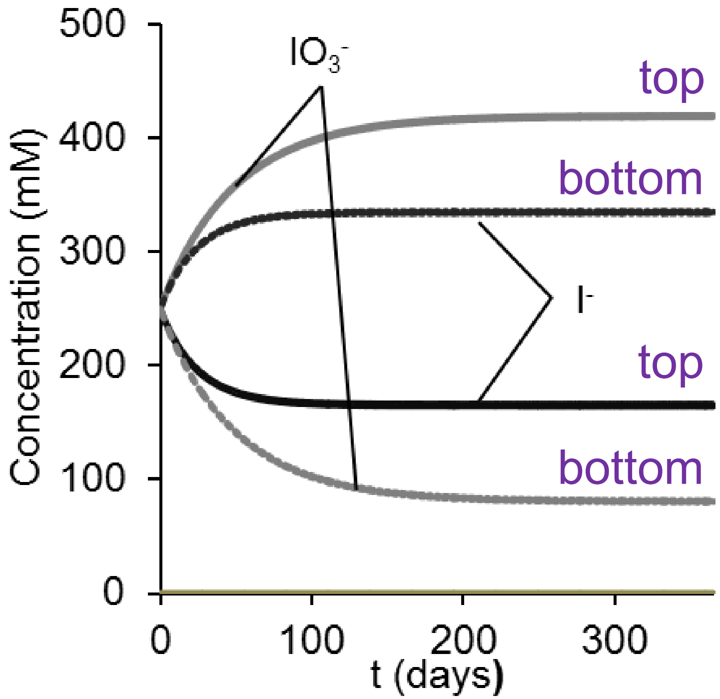
Steady-periodic conditions reached with zero convection; reactor will operate indefinitely

Rohini Bala Chandran
Mechanical Engineer
(LBNL Postdoc)

- ✓ Operates at a maximum 1% STH efficiency
- ✓ Beer's Law for BiVO$_4$ and Rh:SrTiO$_3$; near-ideal photodiodes
- ✓ State-of-the-art electrocatalysis & Butler–Volmer parameters
- ✓ Sunlight absorption by Q/QH$_2$ redox shuttle
- ✓ Non-H$^+$ counterion for redox shuttle (adjustable pH)
- ✓ Separator thickness and porosity limit H$_2$/O$_2$ crossover

Accomplishments: Go, with IO_3^-/I^-





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Rohini Bala Chandran
Mechanical Engineer
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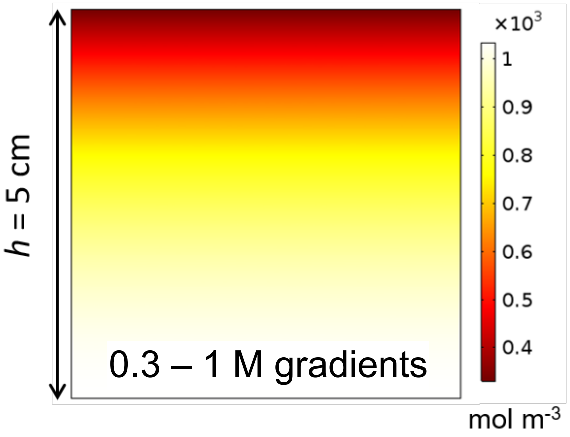
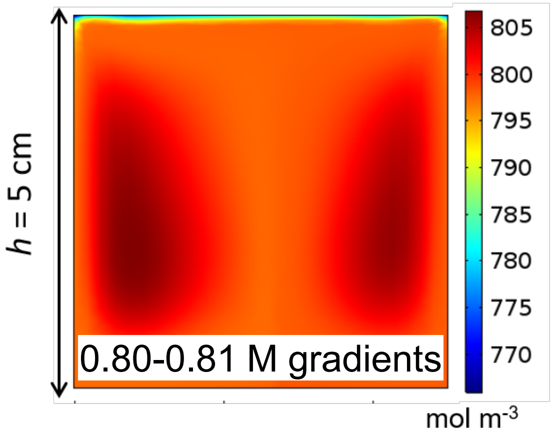
- ✓ Beer's Law for $BiVO_4$ and Rh:$SrTiO_3$; near-ideal photodiodes
- ✓ State-of-the-art electrocatalysis & Butler–Volmer parameters
- ✓ Sunlight absorption by IO_3^-/I^- redox shuttle; all conc. soluble
- ✓ Non-H^+ counterion for redox shuttle (adjustable pH)
- ✓ Separator thickness and porosity limit H_2/O_2 crossover

Accomplishments: Convection

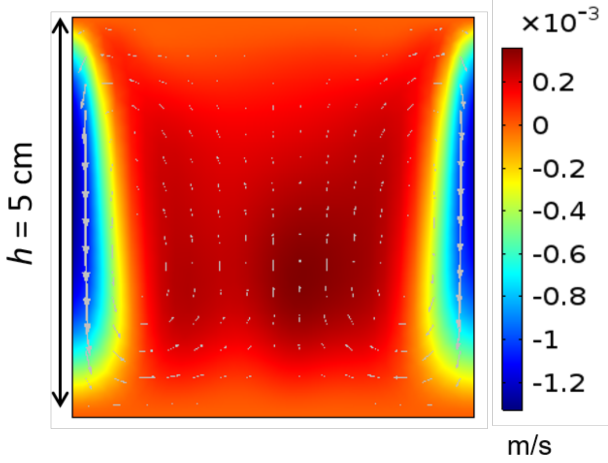
Concentration Profiles with Diffusion Only



Concentration Profiles with Natural Convection



Velocity Profiles with Natural Convection



Thermal mixing due to sunlight absorption by water; not in reactor model yet

Rohini Bala Chandran
Mechanical Engineer
(LBNL Postdoc)

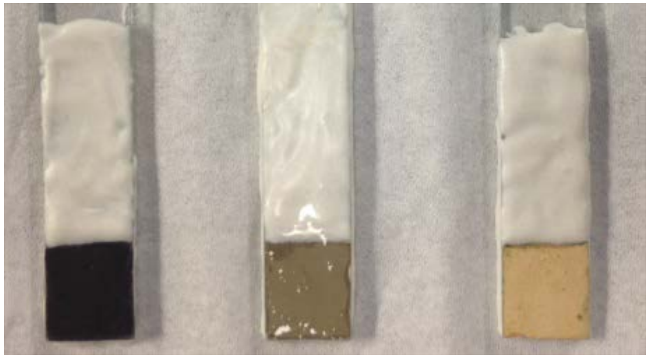
Assumptions

- Neglected spatial density gradients due to inhomogeneous particle concentrations, i.e. $\frac{d\rho}{dc}\frac{dc}{dy}$
- Volumetric heat source, q_s, obtained through sunlight absorption by water (Beer's law at λ > 700 nm)
- Spatially uniform reaction rate, r_i, and boundary flux, N_0, are consistent with a 1% STH efficiency
- Steady-state conditions evaluated without diurnal illumination

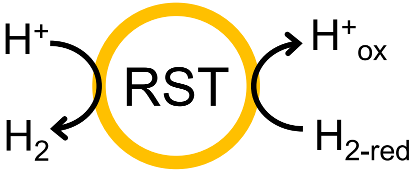
Approach: Milestones

Description of Milestone	Due Date (Quarter)	Percentage Complete
Task 1.0 Numerical modeling and simulations of new reactor design		
M1.1.2 To the model, add advanced semiconductor charge transport, i.e. generation and recombination in the bulk and at surfaces. **(AH) – effective reverse saturation reaction rate implemented**	August 1, 2016 (**Q4**)	**100%**
D1.1.1 Go/No-Go Decision: Using 80% less pipes and 80% less pumping energy, verify 1% η_{STH}. **(AH, AI) – sustainable reactor demonstrated, with no required pumps or pipes**	August 1, 2016 (**Q4**)	**100%**
M1.1.3 To the model, add electromagnetic wave propagation, thermal effects, and multi-phase flow. **(AH, AI) – each of these physical processes has been implemented in part**	August 1, 2017 (**Q8**)	80%
Task 2.0 Experimental evaluation of chemicals, materials, and reactors		
M2.3.1 Identify material(s) that operate at a rate consistent with > 1% η_{STH}, in any form factor and using any redox couple. **(AJ, AG) – $BiVO_4$ with aqueous electrolyte & Rh:$SrTiO_3$ with redox shuttle**	February 1, 2017 (**Q6**)	**100%**
M2.3.2 Demonstrate > 1% η_{STH} in electrode form factor. **(AJ, AG) – 0.1% η_{STH} demonstrated using Rh:$SrTiO_3$ and $BiVO_4$; alternative HER particles, syntheses, and dopants are being explored**	May 1, 2017 (**Q7**)	25%
M2.4.1 Demonstrate > 3 L H_2 (and > 1.5 L O_2) from 8 hours of solar illumination. **(AJ, AG, AH, AI) – built and tested model reactor with 10x smaller illumination area than final deliverable; detected H_2 from smaller reaction vessel using mass spectrometry**	February 1, 2018 (**Q10 / end**)	15%

Accomplishments: Rh:$SrTiO_3$ HER

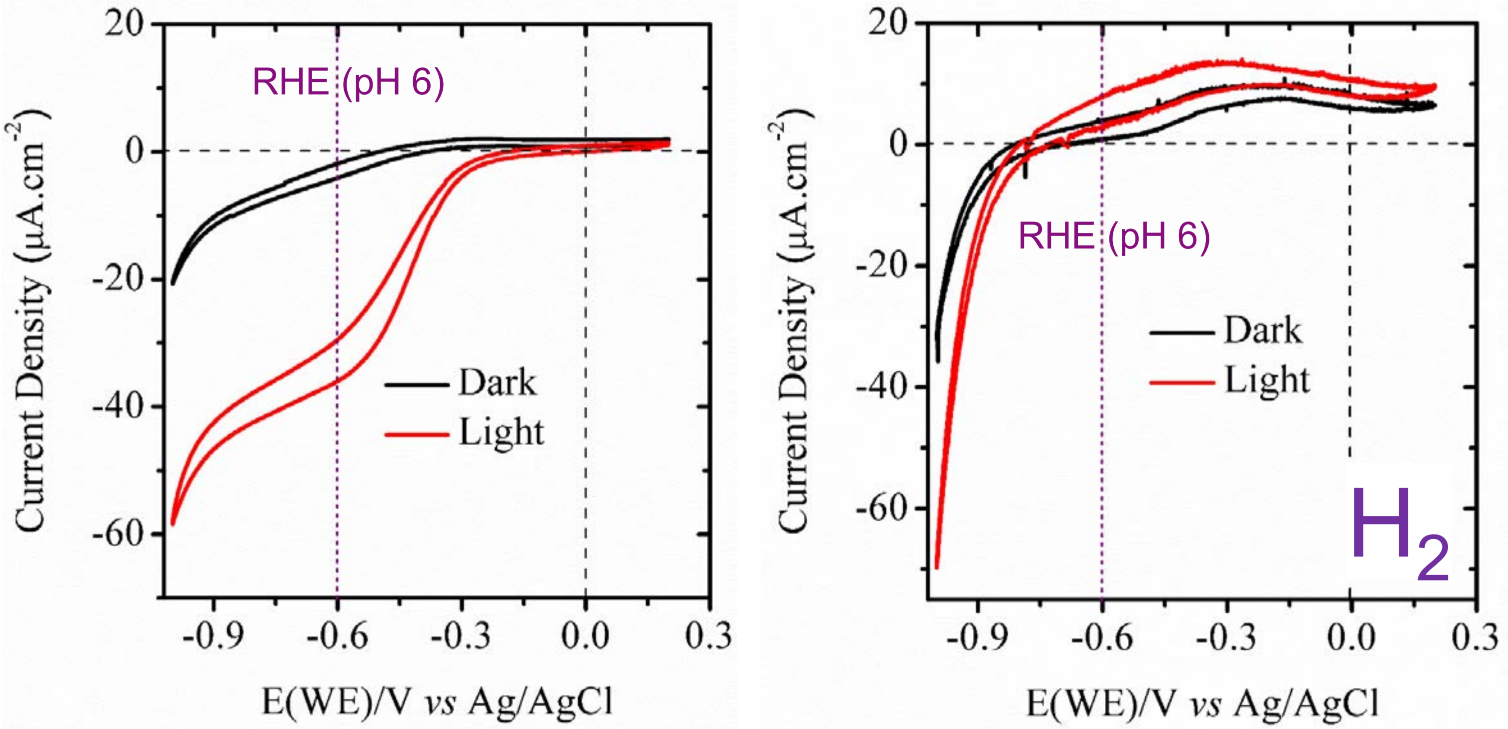


(XPS, UPS, SEM, EDS, XD, DRS, Raman, DLS)



- Rh:$SrTiO_3$ state-of-the-art HER nanoparticle material
- Holes oxidize H_2 prior to being collected in the circuit

Selective reactivity (e.g. no H_2 oxidation) is a big challenge for photocatalysts

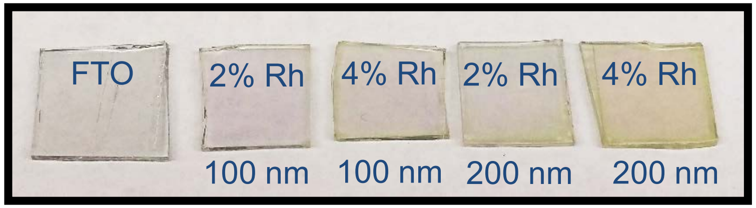


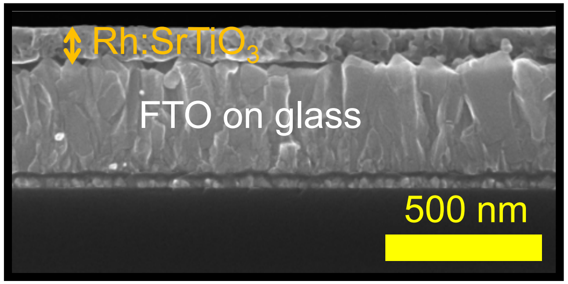
Houman Yaghoubi
Electrical Engineer
(UCI Postdoc)

Accomplishments: Rh:SrTiO$_3$ HER

PC Method:

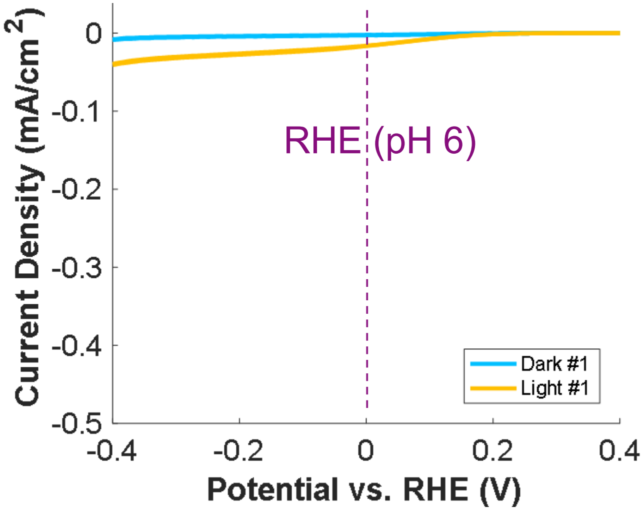
Thin Films:

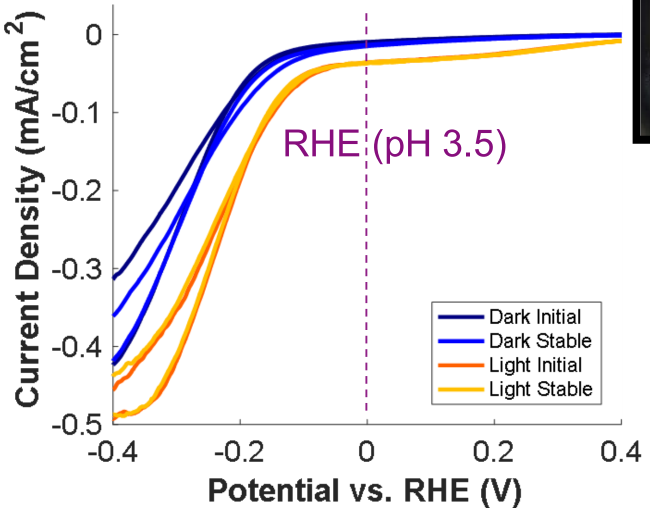




FG Anneal:

Reproducible photocathodic behavior, in the absence of H_2



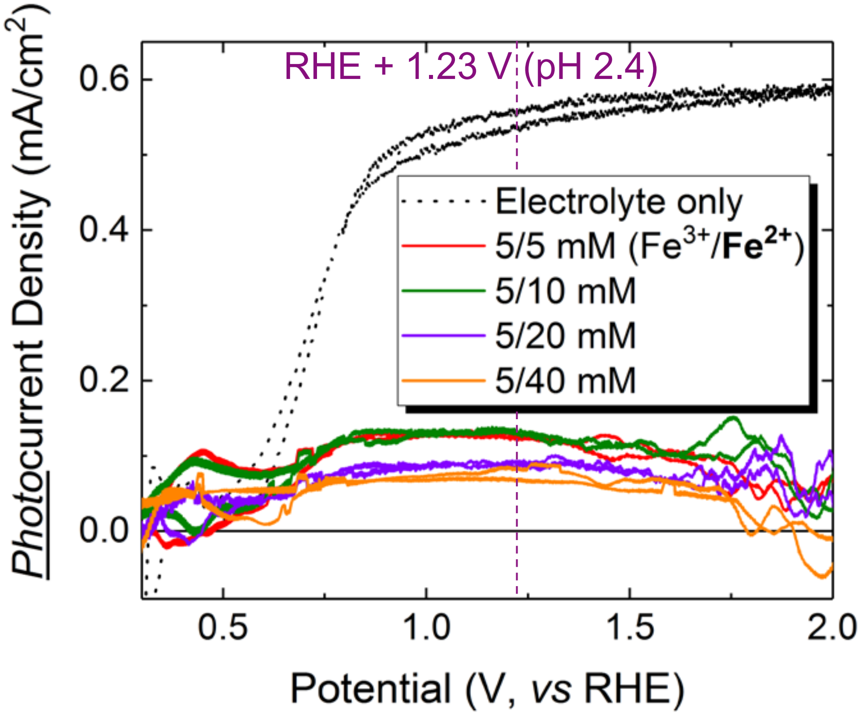


Sam Keene
Physicist
(UCI Ph.D. Student)

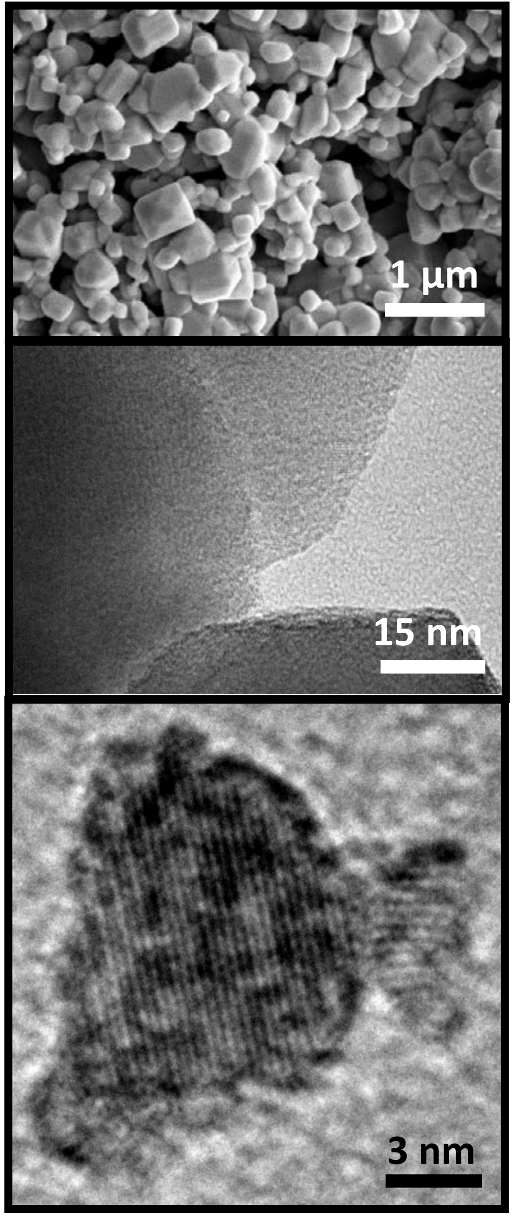
* pH 6, 3.5, 2.4 are most relevant from observations, and from literature precedent

Accomplishments: WO_3 OER

- WO_3 state-of-the-art OER particle material in acid
- *J–E* behavior is very similar with and without O_2
- Interesting photocurrent behavior with added **Fe(II)** redox shuttle (data reported here is light current density minus dark current density)



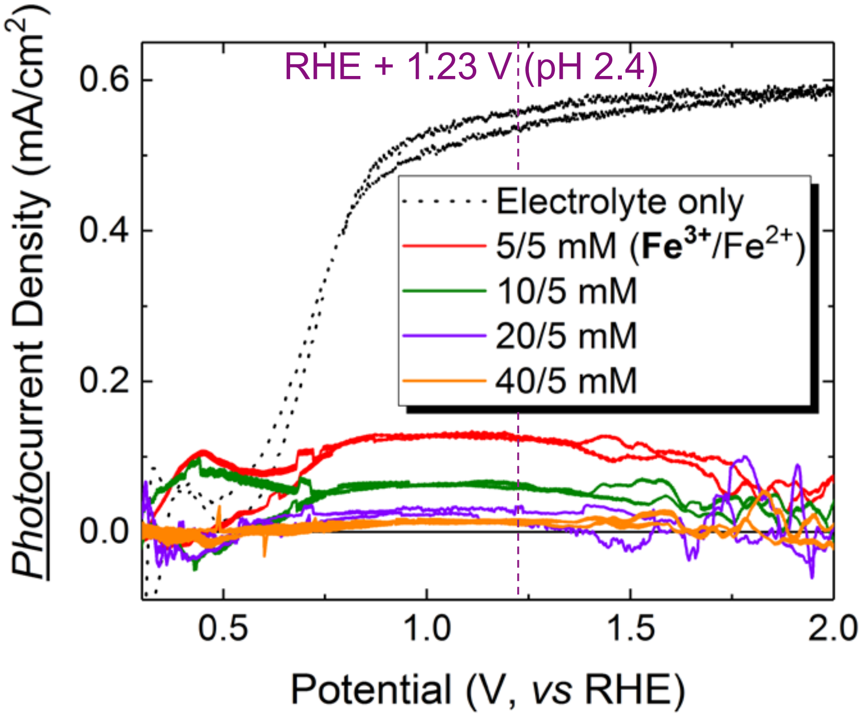
Fe^{2+} is likely oxidized at illuminated WO_3, but photocurrent decreases



William Gaieck
Materials Scientist
(UCI Ph.D. Student)

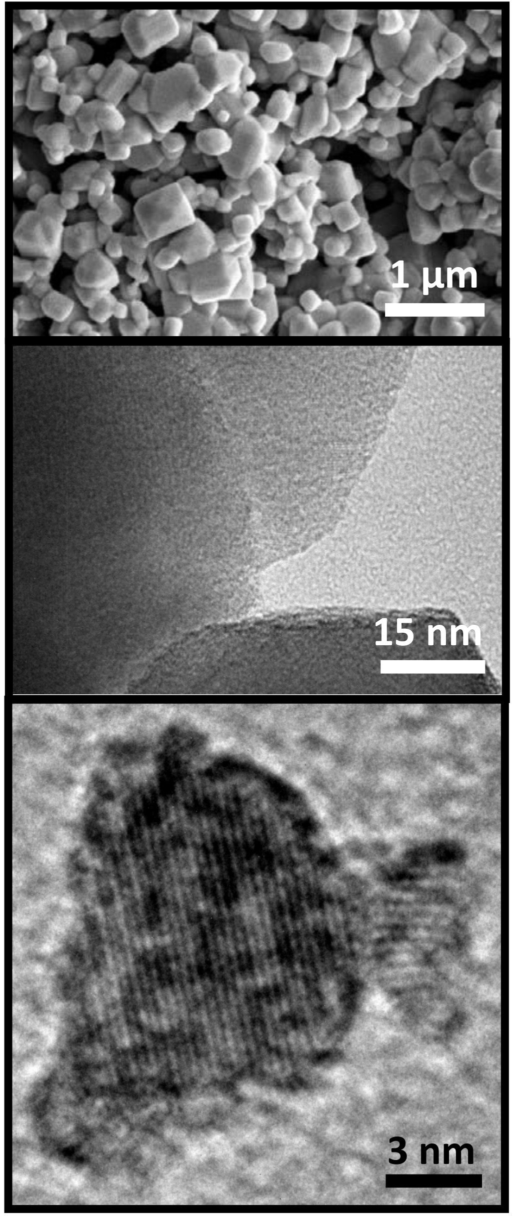
Accomplishments: WO_3 OER

- WO_3 state-of-the-art OER particle material in acid
- *J–E* behavior is very similar with and without O_2
- Interesting photocurrent behavior with added **Fe(III)** redox shuttle (data reported here is light current density minus dark current density)



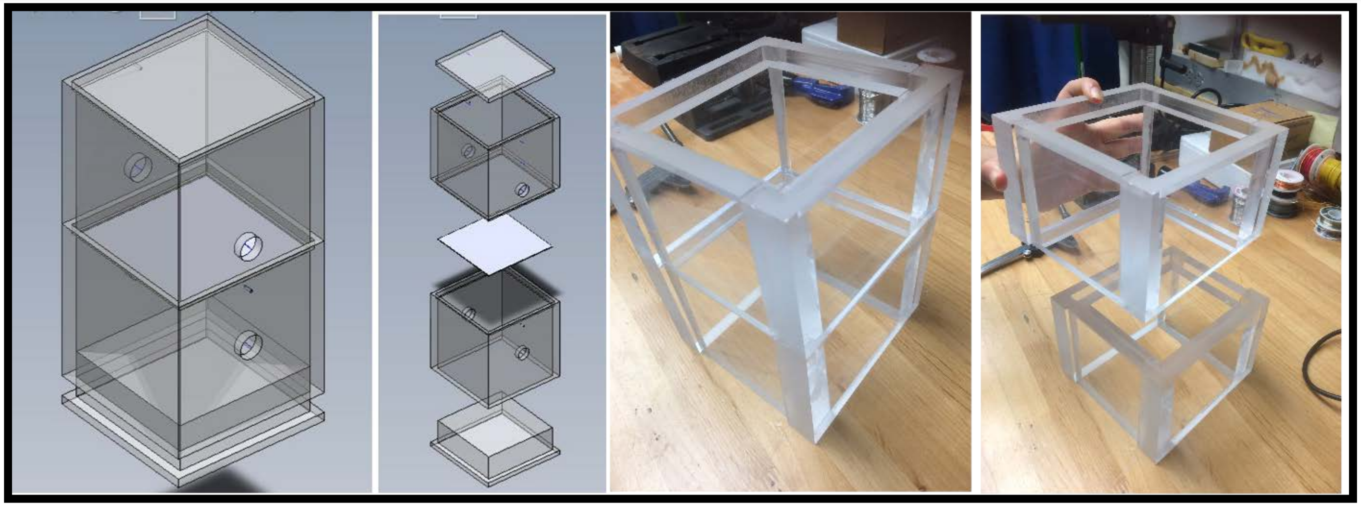
Fe^{3+} very efficiently scavenges photogenerated electrons at WO_3

William Gaieck
Materials Scientist
(UCI Ph.D. Student)



Accomplishments: Reactor

Separators assessed in leak-free Plexiglas prototype reactor (4 x 4 x 8”)



Kevin Tkacz
Materials Scientist
(UCI Ph.D. Student)

Response to previous year reviewers' comments

"… it is unclear how much of the boost in efficiency and projected cost reduction can be attributed to the "new design" and how much would be attributed to having better-performing photocatalysts"

> A techno-economic analysis using the H2A tool was conducted and it is clear that the new design saves significantly on cost, irrespective of the photocatalysts which are of course completely required for attaining this cost benefit.

"The funding of research on Type 2 PECs that is likely not to lead to a practical implementation is not advised. EERE is fully responsible for selecting projects based on real or anticipated contributions to achievable designs—those with the greatest potential for translation to practical applications."

> Techno-economic analyses suggest that most PEC designs will not likely make a practical impact. The (new) Type 2 design is likely the most credible reactor design for practical PEC application.

"Project weaknesses include a lack of important understanding of particle stability, membrane integrity, and particle quantum yield."

> In general, these are not within the proposed scope of work. Particle stability is a concern, but is a lesser concern given the poor quantum yields of particles to date. We are trying to understand the causes of these poor efficiencies and remedy them. Membrane integrity is not a concern; we have tested several filtration/osmosis membranes and they are all stable; the challenge is "baggie" transparency which we are exploring.

Collaborations

Primary team members *(funded)*

- Lawrence Berkeley National Laboratory (Federal Lab) & Joint Center for Artificial Photosynthesis (DOE Hub)
  - **Adam Weber (sub-recipient)**: Core numerical device-physics modeling and simulation effort, specifically chemical engineering and multi-physics
- California Institute of Technology (University) & Joint Center for Artificial Photosynthesis (DOE Hub)
  - **Chengxiang Xiang (sub-contracted advisor)**: Expertise in numerical device-physics modeling and simulation effort, specifically semiconductor physics and ray tracing

Additional team members with materials synthesis expertise *(unfunded)*

- Tokyo University of Science, **Akihiko Kudo ($Rh:SrTiO_3$, $BiVO_4$)**

Remaining Challenges and Barriers

Task 1.0 Numerical modeling and simulation of new reactor design

- Introduce complex fluid flow to enable simulation of forced convection, e.g. by electrolyte pumping.
- Introduce advanced optical phenomena to more accurately model E&M and particle photophysics.
- Introduce thermal effects to the full reactor model and investigate effects of natural convection.
- More accurately implement photocatalyst reactivity by modeling individual reactions on particles instead of baggie ensemble behavior as an ideal diode plus empirical Bulter–Volmer kinetics.

Task 2.0 Experimental evaluation of chemicals, materials, and reactors

- Observe redox shuttle concentrations in a prototype reactor that are consistent with numerical simulations under simulated day–night cycling as an indicator of the accuracy of the device physics models.
- Identify material(s) that operate at a rate consistent with > 1% η_{STH} in electrode form factor and as particle suspensions, as prerequisites to the final deliverable.

Final Deliverable: Demonstrate > 3 standard L of H_2 (and > 1.5 L of O_2) from 8 hours of solar illumination.

Any proposed future work is subject to change based on funding levels.

Proposed Future Work

Project Objective: **Experimentally validate** a *new design* for scalable solar-H_2 technologies using laboratory-scale prototype particle suspension reactors

Description of Milestone – Solution	Due Date (Quarter)	Percentage Complete
Task 1.0 Numerical modeling and simulation of new reactor design		
M1.1.3 To the model, add electromagnetic wave propagation, thermal effects, and multi-phase flow – **Introduce multiple physics by coding them into the current model and validating results**	August 1, 2017 (**Q8**)	80%
Task 2.0 Experimental evaluation of chemicals, materials, and reactors		
M2.3.2 Demonstrate > 1% η_{STH} in electrode form factor **– Using thin-film and mesoporous electrodes, introduce electrocatalysts by photochemical deposition**	May 1, 2017 (**Q7**)	25%
M2.4.1 Demonstrate > 3 standard L of H_2 (and > 1.5 L of O_2) from 8 hours of solar illumination **– Using electrodes and free-floating particles, assess the impacts that redox shuttles have on the rate of H_2 evolution; introduce selective catalysis through interfacial engineering of light absorbers and catalysts; combine particles, prototype reactors, and redox shuttles and measure rate of H_2 evolution**	February 1, 2018 (**Q10 / end**)	15%

Any proposed future work is subject to change based on funding levels.

Project Summary

Project Objective: **Experimentally validate** a *new design* for scalable solar-H_2 technologies using laboratory-scale prototype particle suspension reactors

Relevance	Techno-economic analyses of particle suspension reactors with side-by-side compartments suggest that H_2 cost may be rather inexpensive.
Approach	Stack the compartments to realize the tandem efficiency advantage and shorten the mass transport distance so that fewer pumps and pipes are required to circulate the electrolyte.
Technical Accomplishments	Using a validated device physics model, demonstrated stable operation of a tandem reactor operating at a 1% STH efficiency assuming most relevant physics. Also, used bipolar electrochemistry to deposit electrocatalysts and measure the photoresponse of single-to-few particles jammed in a plastic sheet. Also, synthesized and characterized efficient photoelectrodes consisting of Rh-modified $SrTiO_3$, WO_3, or $BiVO_4$ and for each of these, demonstrated photocurrent at a rate consistent with a 1% STH efficiency. Developed prototype reactors and techniques to locally assess redox shuttle concentration *in situ*.
Collaborations	*Weber* / *Xiang* for numerical modeling; *Kudo* for materials synthesis.
Proposed Future Work	Add additional device physics to the numerical models and synthesize high quality metal-oxide particles that attain a 1% STH efficiency.

Technical Backup Slides

Relevance: Motivation

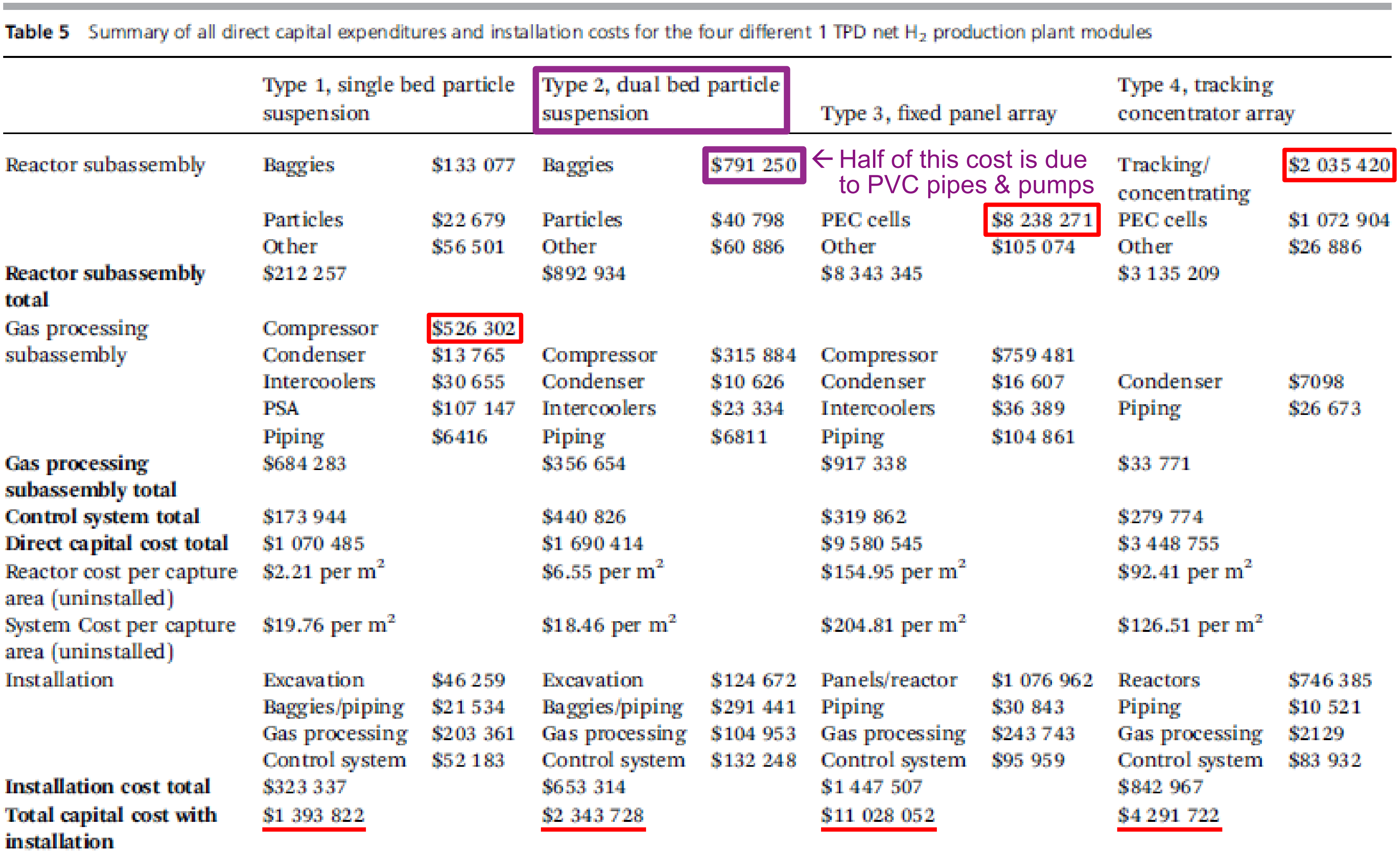


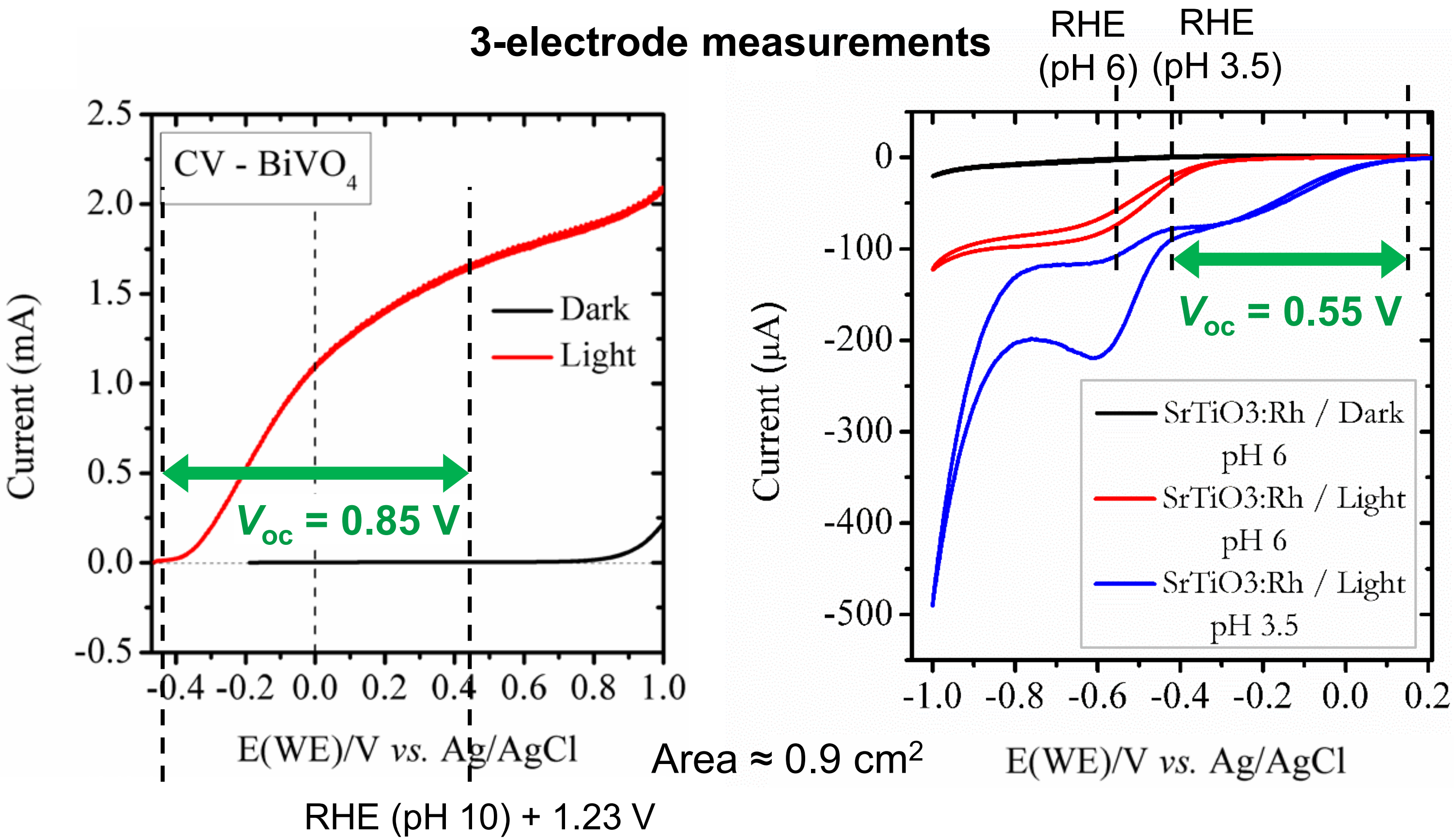
Table 5 Summary of all direct capital expenditures and installation costs for the four different 1 TPD net H_2 production plant modules

	Type 1, single bed particle suspension		Type 2, dual bed particle suspension		Type 3, fixed panel array		Type 4, tracking concentrator array	
Reactor subassembly	Baggies	$133 077	Baggies	$791 250			Tracking/ concentrating	$2 035 420
	Particles	$22 679	Particles	$40 798	PEC cells	$8 238 271	PEC cells	$1 072 904
	Other	$56 501	Other	$60 886	Other	$105 074	Other	$26 886
Reactor subassembly total	$212 257		$892 934		$8 343 345		$3 135 209	
Gas processing subassembly	Compressor	$526 302						
	Condenser	$13 765	Compressor	$315 884	Compressor	$759 481		
	Intercoolers	$30 655	Condenser	$10 626	Condenser	$16 607	Condenser	$7098
	PSA	$107 147	Intercoolers	$23 334	Intercoolers	$36 389	Piping	$26 673
	Piping	$6416	Piping	$6811	Piping	$104 861		
Gas processing subassembly total	$684 283		$356 654		$917 338		$33 771	
Control system total	$173 944		$440 826		$319 862		$279 774	
Direct capital cost total	$1 070 485		$1 690 414		$9 580 545		$3 448 755	
Reactor cost per capture area (uninstalled)	$2.21 per m^2		$6.55 per m^2		$154.95 per m^2		$92.41 per m^2	
System Cost per capture area (uninstalled)	$19.76 per m^2		$18.46 per m^2		$204.81 per m^2		$126.51 per m^2	
Installation	Excavation	$46 259	Excavation	$124 672	Panels/reactor	$1 076 962	Reactors	$746 385
	Baggies/piping	$21 534	Baggies/piping	$291 441	Piping	$30 843	Piping	$10 521
	Gas processing	$203 361	Gas processing	$104 953	Gas processing	$243 743	Gas processing	$2129
	Control system	$52 183	Control system	$132 248	Control system	$95 959	Control system	$83 932
Installation cost total	$323 337		$653 314		$1 447 507		$842 967	
Total capital cost with installation	$1 393 822		$2 343 728		$11 028 052		$4 291 722	

← Half of this cost is due to PVC pipes & pumps

Directed Technologies, Inc., DOE Report, 2009 & Pinaud, …, Ardo, …, Jaramillo, *Energy Environ. Sci.*, 2013, *6*, 1983
DOE–EERE, H2A Analysis, http://www.hydrogen.energy.gov/h2a_production.html

Prior Accomplishments: Materials


3-electrode measurements

RHE (pH 6)

RHE (pH 3.5)

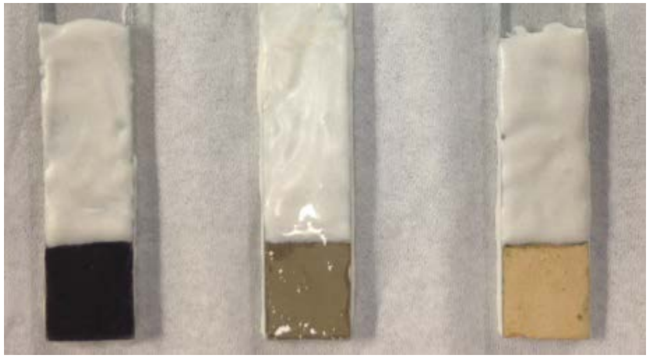
Area ≈ 0.9 cm^2

RHE (pH 10) + 1.23 V

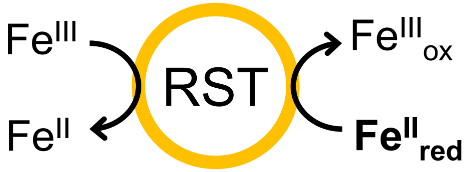
Houman Yaghoubi
Electrical Engineer
(UCI Postdoc)

Rh-modified $SrTiO_3$ and $BiVO_4$ can generate > 1.23 V, but efficiency is limited by Rh:$SrTiO_3$ $J \approx 0.1$ mA cm^{-2}

Accomplishments: Rh:SrTiO$_3$ HER



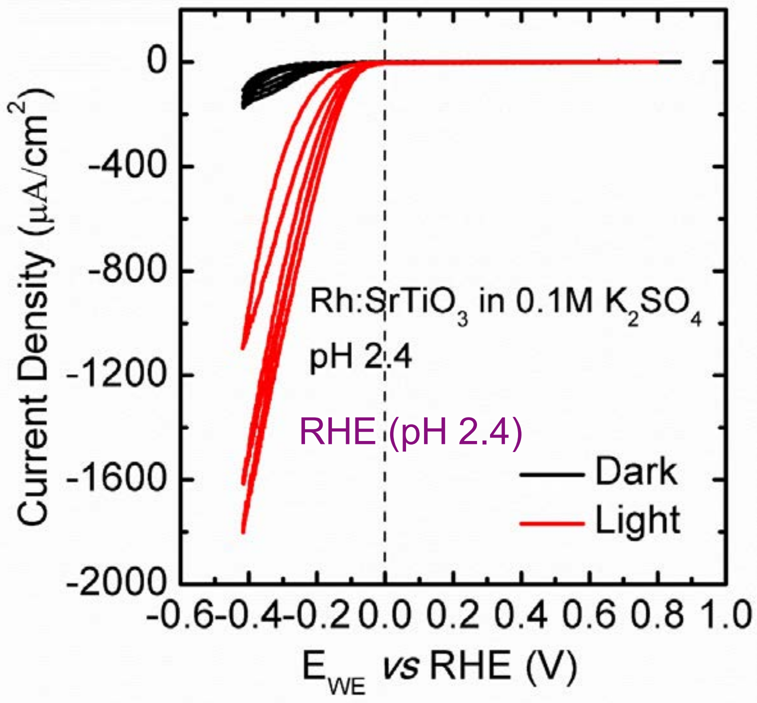
(XPS, UPS, SEM, EDS, XD, DRS, Raman, DLS)

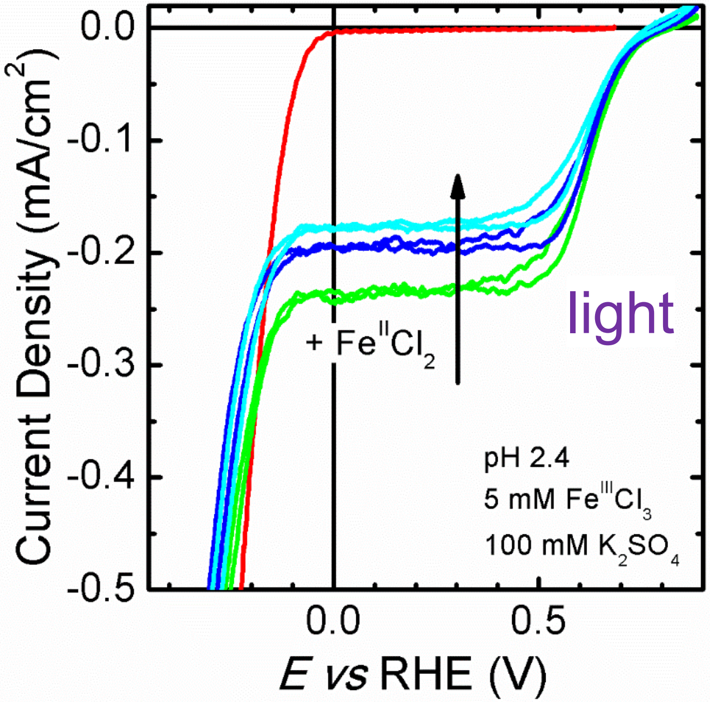


- Electrons easily reduce Fe(III)
- Hole oxidation reactions of Fe(II) not noticeable

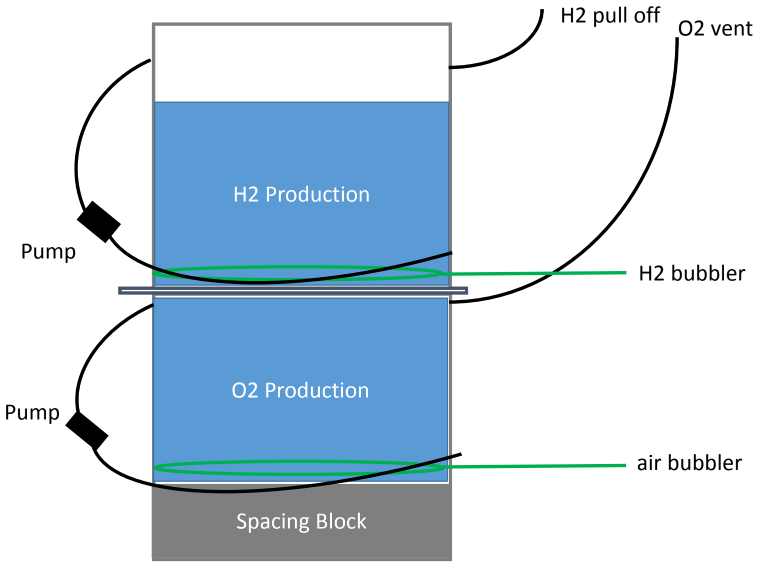
Fe(II) attenuates rate of Fe(III) oxidation for more selective reactivity

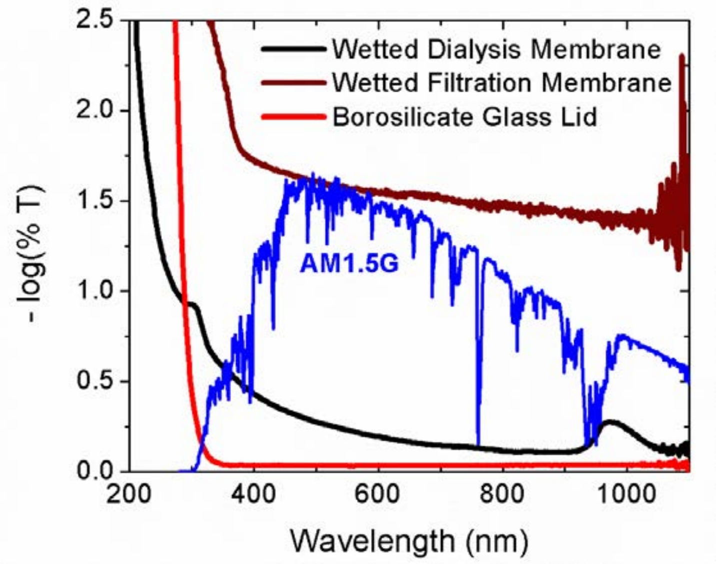
Houman Yaghoubi
Electrical Engineer
(UCI Postdoc)





Accomplishments: Separators



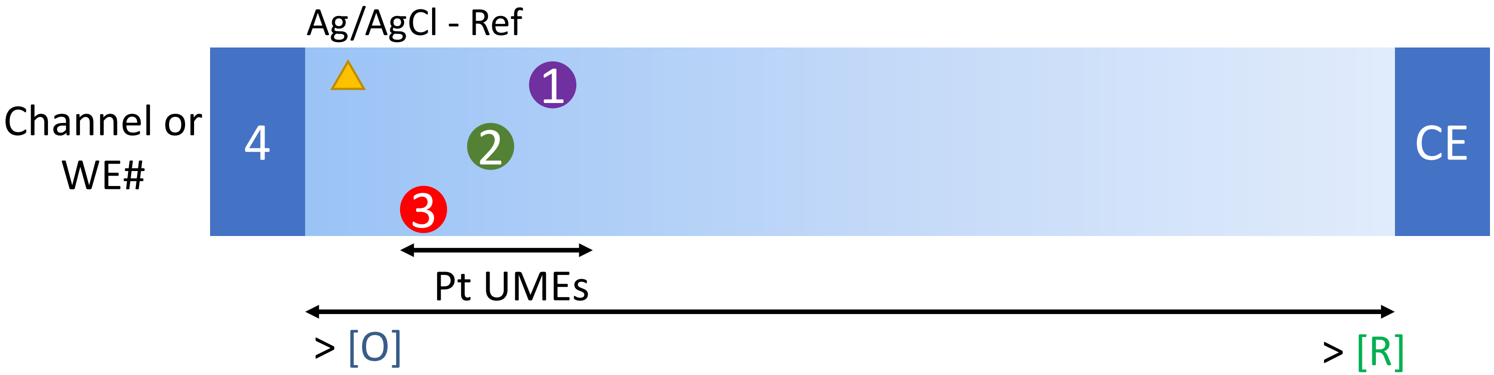


	Dialysis Membrane	Snyder ultrafiltration Membrane	Genpore Plastic	Polyvinyl Membrane
Transparent	🟩	Opaque	Opaque	🟩
Dye Diffusion	Slow	🟩	No diffusion	🟩
NP diffusion	Some leakage	–	–	Macroscopic Holes
Physically Robust	🟩	🟩	🟩	Fell apart

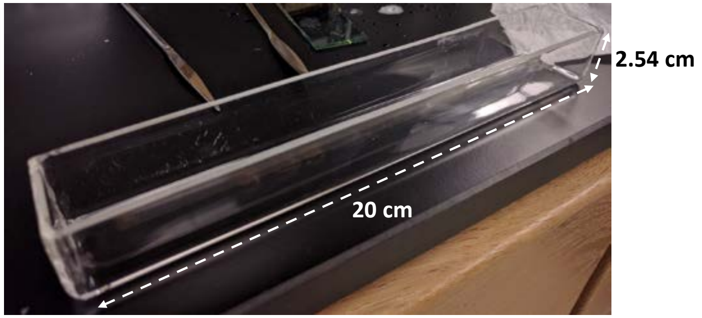
Kevin Tkacz
Materials Scientist
(UCI Ph.D. Student)

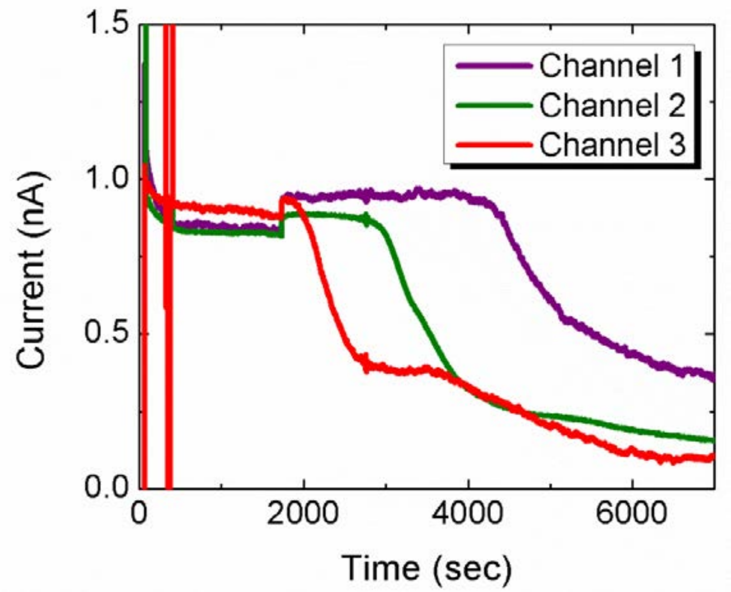
A suitable nanoporous separator has not been identified

Accomplishments: *In Situ* EChem



Previously spatial spectroscopic probing, and now local electrochemical probing too





* During oxidation at WE(4), oxidative current at each UME drops off as the boundary/ diffusion layer grows

William Gaieck
Materials Scientist
(UCI Ph.D. Student)