FuelCell Energy

Reformer-Electrolyzer-Purifier (REP)

for Production of Hydrogen

2015 AMR (Annual Merit Review), Washington DC

P.I. / Presenter -- Fred Jahnke

FuelCell Energy, Inc.

June 11, 2015

Project ID #: PD112

Ultra-Clean, Efficient, Reliable Power

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Overview

Timeline

- Start: October 2014
- End: September 2016

Budget

- Total Budget: $1,250,509
  - Total Recipient Share: $254,215
  - Total Federal Share: $996,294

Barriers

Barriers to hydrogen infrastructure:

- **High cost**
  - High capital costs for distributed production
  - High transportation costs for central units
- **Limited areas of production**
  - Emissions limit potential sites
- **Scalability of production to local demand**
- **Production efficiency**

Funded Partners

- UC Irvine National Fuel Cell Center

Impact of REP Technology

1. Lower cost hydrogen
   - Can meet DOE Target - Long term H2 less than 2 $/kg
2. Low carbon emissions
   - Can meet DOE Target - CO2 emissions less than 5,000 g/gge
   - System utilizes waste heat
   - 100% conversion of CH4 with recycle
   - Low power high temperature electrolysis removes CO2 and provides 25% additional H2
   - 100% H2 recovery with recycle
3. ~Zero NOx, CO, SOx emissions when integrated with DFC® fuel cell
4. System fully scalable
   - Number of cells determines capacity
   - Home fueler (2kg/d) to large scale 16,000 kg/d
5. Manufacturing facilities already in place and operating
   - Will use same components currently being manufactured for DFC® fuel cells

Approach

- Use existing FuelCell Energy MCFC (molten carbonate fuel cell) components
- Operate MCFC in electrolyzer mode as CO2 pump
  - Phase 1 – single cell testing and model development
    Long term testing / life determination
  - Phase 2 – Multi cell stack testing and thermal management
  - Optimization of configuration options using H2A model (UCI support) and commercialization plan
- Integrate input from potential users and stakeholders
  - Integration with DFC® operating fuel cell can provide heat and feed preparation needed by REP
  - Other sources of waste heat
  - H2 users, low and high pressure

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Project Milestones

Task	Description	Verification
Single Cell Parameter - Testing	**Testing unit is started.**	**Testing Started. Unit hot and initial preliminary data available.**
Single Cell - Base Case	**Single cell unit tested under base case operating conditions**	**Base case cell operations at 130 mA/cm2 with feed gas composition corresponding to a 1130° F reforming temperature will increase 30% in the H2 production and a 20% in H2 purity compared to no electrolysis.**
Reconfirm attractive economics	System optimized and the attractive economics confirmed.	Updated HMBs issued to UCI. Validate economics indicate a H2 production cost of 1.4 to 2.2 $/kg H2.
Go/No-Go Decision	Test results meet targets given in SOPO	Single cell test stand provides data which confirms passing of go/no go conditions described in SOPO.

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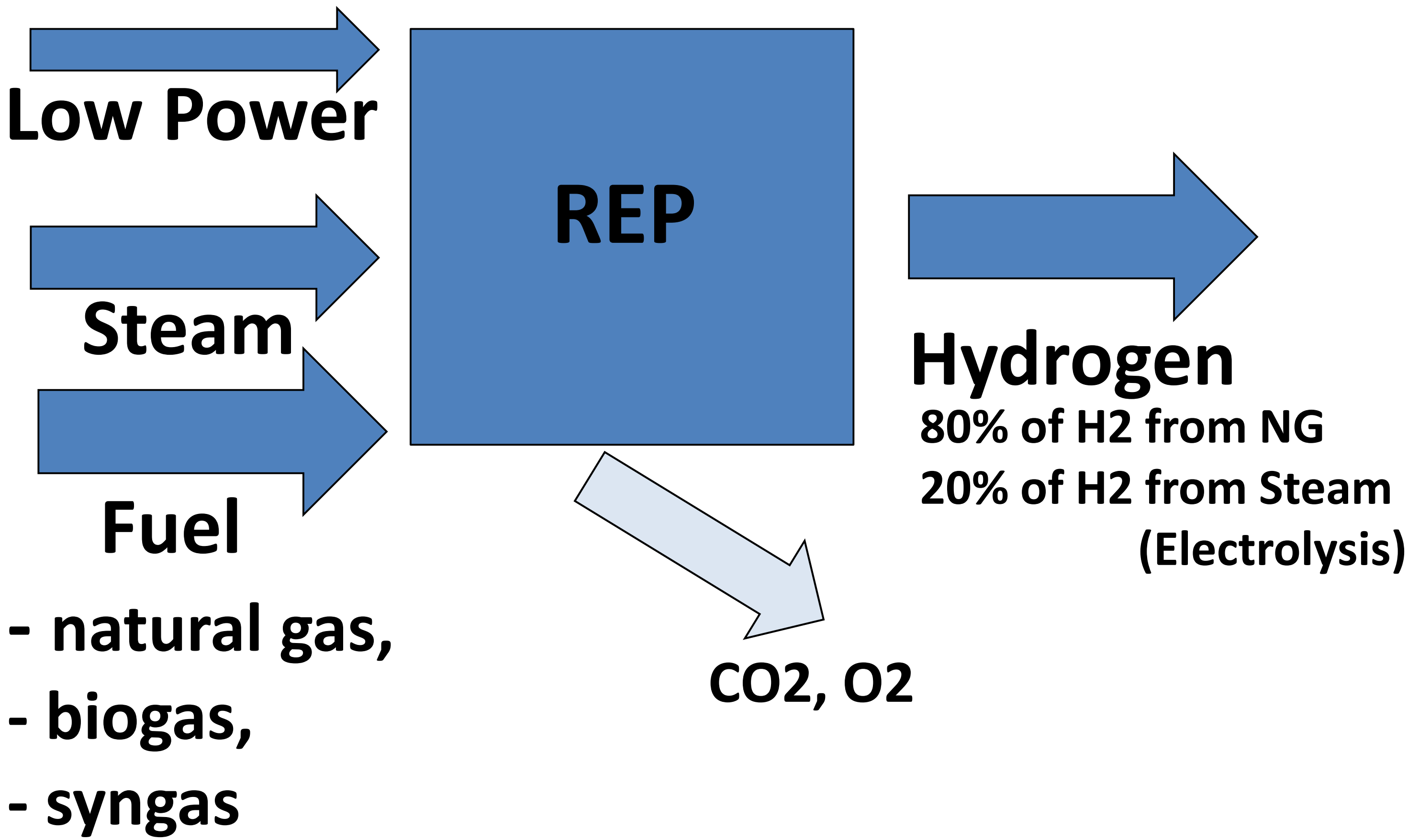
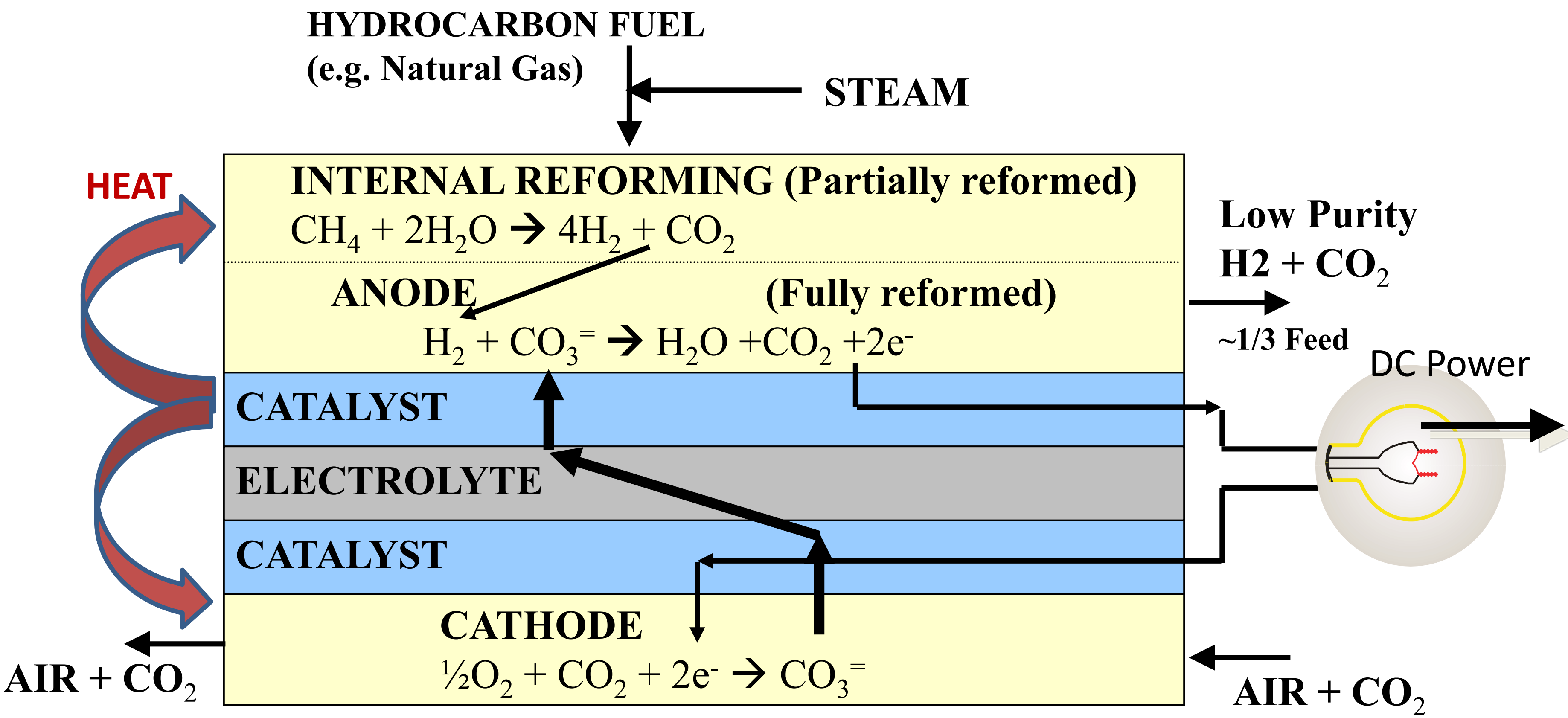
Project Milestones

Task	Description	Verification
Build large scale REP	The large scale unit construction started.	PO for >85% of parts issued.
Long Term Testing	Single Cell Long term testing	Tests show < 10%/yr performance degradation.
Commercial scale REP tests	The commercial scale testing started.	Unit operating and Initial test results issued. Demonstrate 100 kg H2/day production rate.
Refine HMB's and economics	HMB's and economics updated based on test results.	Commercial test results completed. Updated HMB's issued to UCI
Continue Commercial scale REP tests	Commercial scale REP unit demonstrate	In-house test stand confirms CO2 emissions lowered 40%, production of 100 kg H2/day, and degradation rate less than 1.25%/1000 hr.
Draft final report for comments	Issue final report	Draft Final Report Issued for comments. Hydrogen production cost of $2/kg H2,

REP Basic Operation

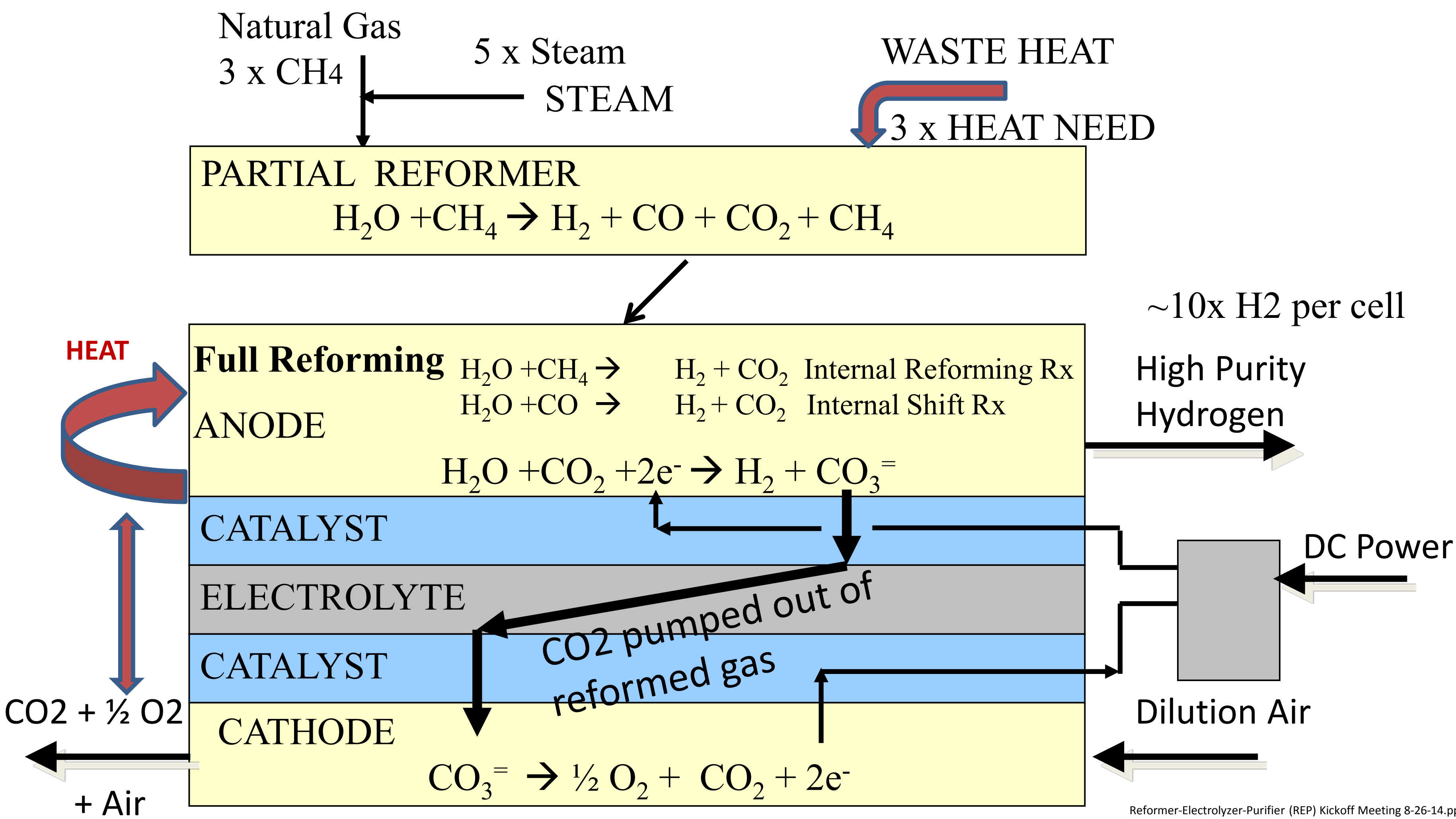


Standard DFC® Fuel Cell



REP Cell Technology

(CO2+O⁼ Pump)



Reformer-Electrolyzer-Purifier (REP) Kickoff Meeting 8-26-14.pptx

10 x H2 per cell generated, external heat source is needed

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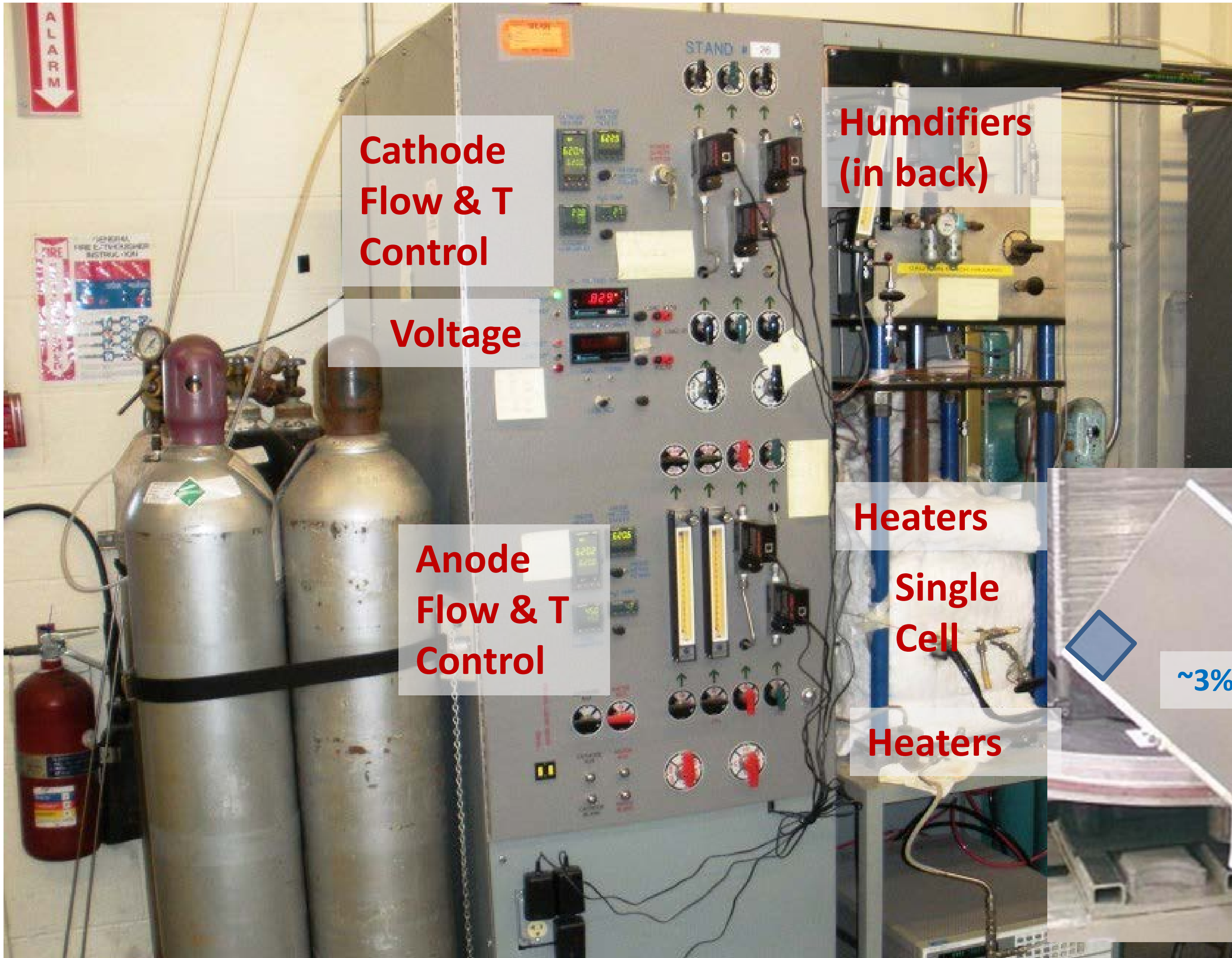
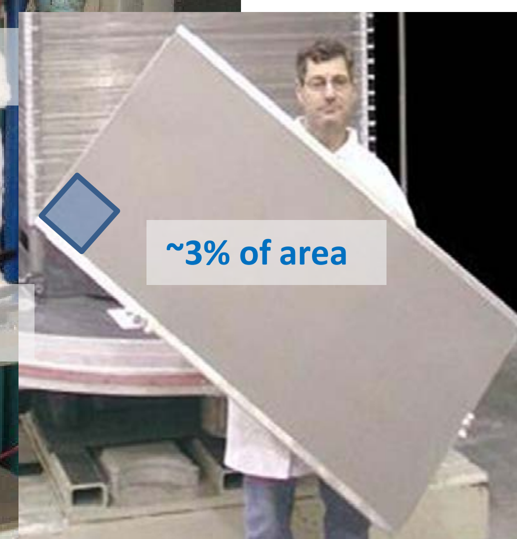
REP Single Cell Test Facility





Future REP Stack Test Facility

2000 kg/d

100 kg/d

Accomplishments

Phase 1

1. Single Cell Performance Determined

a) Voltage vs Purity
b) Power consumption
c) Sweep Gas
d) Detailed performance model

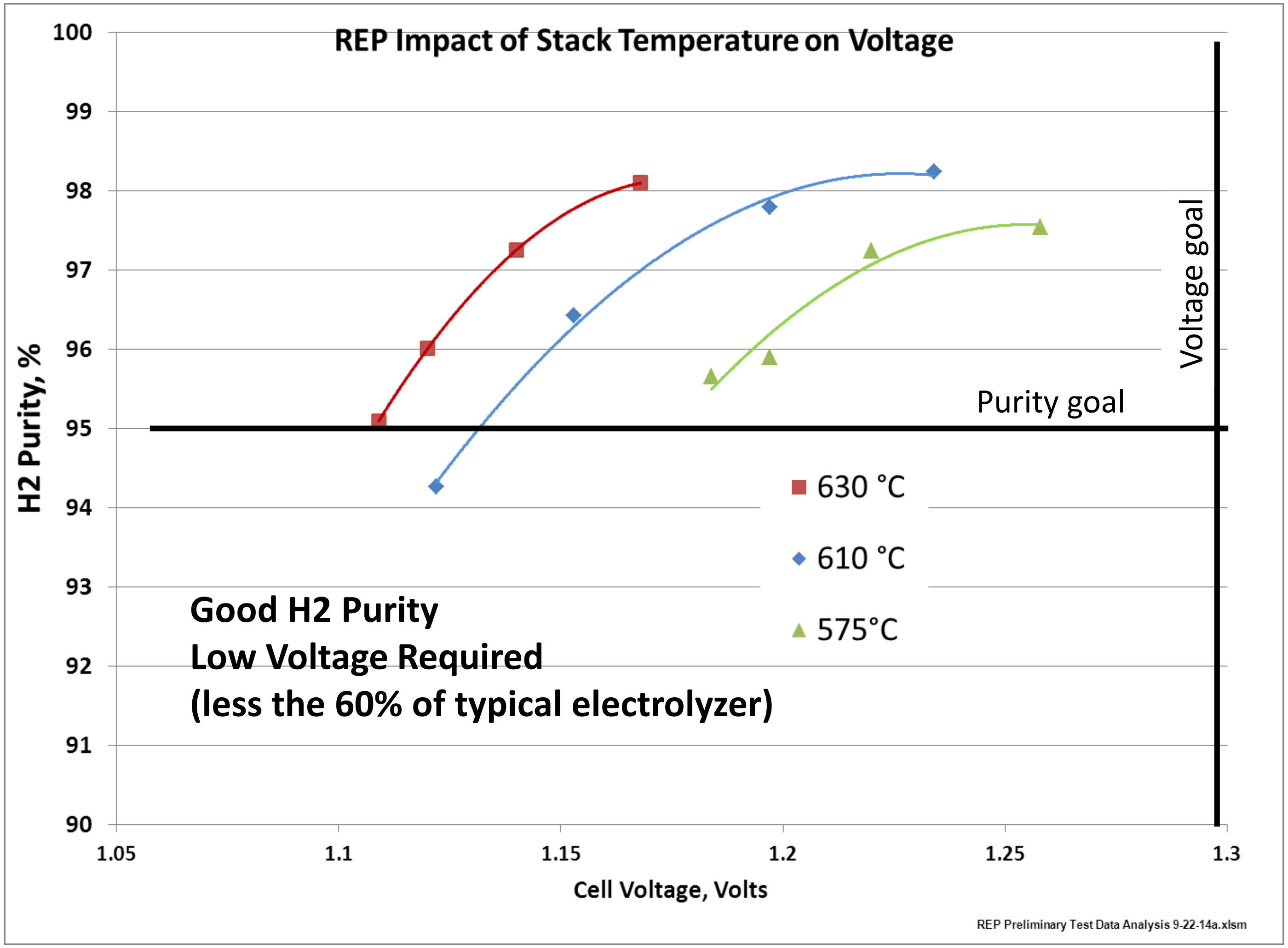
2. Confirmed life of fuel cell (continuing)

a) Long term operation of cell 1500 hrs to date
b) Low Degradation rate so far

3. Defined system options (continuing)

a) Integrated with DFC
b) Standalone system
c) Alternate feedstocks (gasifier, ADG, waste gas)

REP Single Cell Performance



Low power consumption confirmed (<1.2 v/cell)

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REP Voltage Model Developed

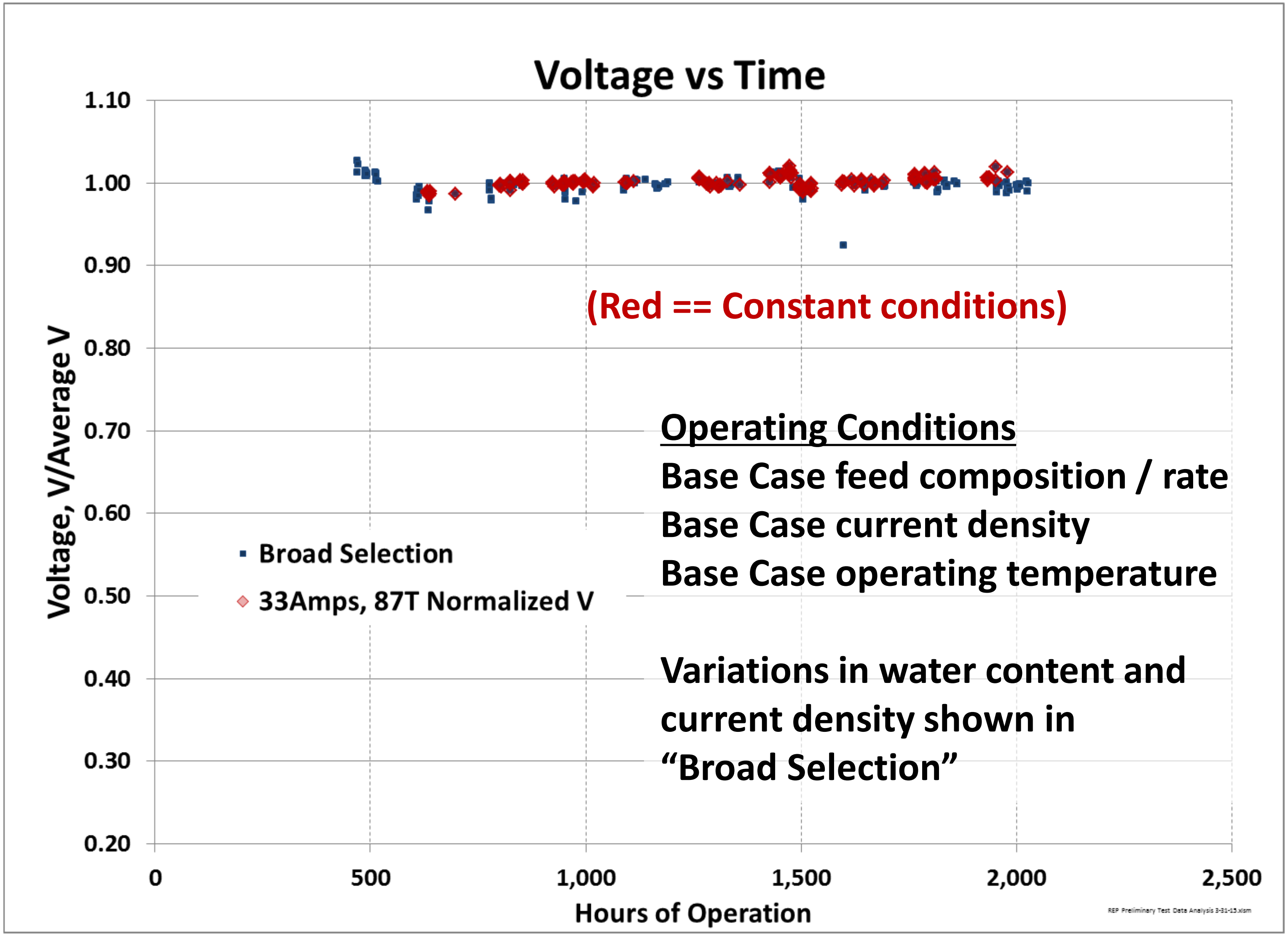
$$E = E_T^o + \frac{RT}{2F} \ln \frac{\chi_{H_2} \chi_{O_2}^{1/2} \chi_{CO_2(c)}}{\chi_{H_2O} \chi_{CO_2(a)}} + \frac{RT}{4F} \ln P$$

Case	Model Voltage	Measured Voltage	Voltage Error
33.5A	1,159	1,170	0.9%
33.5A Low Air Flow	1,163	1,170	0.5%
37A	1,166	1,173	0.6%
37A Low T	1,209	1,220	0.9%
37A High T	1,149	1,140	-0.8%
40A	1,216	1,201	-1.3%
40A N2 Sweep	1,234	1,234	0.0%
40A No Cath Flow	1,271	1,333	4.3%
Average Error	0.07%		
Stnd Deviation	1.01%		
	Error = (Meas V / Calc V) -1		REP Single Cell HMB Summary 10-1-14.xlsm

V_1_	1142.6
E	1028.8
ηcathact_1_	-55.9
ηanact_1_	-28.9
ηconc_1_	-16.1
i * Zir	-40.0
ηnernst	27.1
E_1_	1.0287339
EoT_1_	1.0287607
F_1_	96485.3
i_1_	-1582.1363
iL_1_	8000
iLk_1_	
iLko2c_1_	11257.723
iLkco2c_1_	3958.1632
iLkh2oa_1_	N/A
iLkh2a_1_	8837.9538
iLkco2a_1_	N/A
ka_1_	3.10E-07
kc_1_	3.06E-09
kir_1_	2.15E-06
n_1_	2
nk_1_	
nko2c_1_	0.6
nkco2c_1_	0.4
nkh2a_1_	1
Pc_1_	1.0078587
Qa_1_	19.1
Qc_1_	61.67
Qir_1_	18.11
R_1_	0.0083145
Tc_1_	883.33333
Za_1_	1.826E-05
Zc_1_	3.532E-05
Zir_1_	2.531E-05
Xk_1_	
Xo2c_1_	0.2208908
Xco2c_1_	0.0327162
Xh2oa_1_	0.3637636
Xh2a_1_	0.5523721
Xco2a_1_	0.0474421
Xo2cref_1_	0.125
Xco2cref_1_	0.19
Xh2oaref_1_	0
Xh2aref_1_	0.5
Xco2aref_1_	0
DelGT_1_	-198520.57
ηact_1_	-0.0558881
ηact_1_	-0.0288915
ηconc_1_	-0.0161431
ηconco2c_1_	0.06575
ηconcco2c_1_	0.3362685
ηconch2oa_1_	0
ηconch2a_1_	0.0221303
ηconcco2a_1_	0
vk_1_	
vko2c_1_	0.5
vkco2c_1_	1
vkh2oa_1_	0
vkh2a_1_	1
vkco2a_1_	0
ηnernst	27.08542
Za_1_	182.6
Zc_1_	353.2
Zir_1_	253.1

- Sophisticated Model developed for REP (adapted from MCFC fuel cell model with minor adjustments).
- Model closely matches test data.
- Model allows optimization of system operation and accurate heat and material balances.

Stable Operation



Collaborations

Collaborator – UC Irvine NFCRC

1. **Confirm economics of system**
   a) Develop optimization model
   b) Configuration options
   c) Operating conditions
   d) Sensitivity to prices
   e) Waste heat impact
2. **Large cell modeling**
   a) Temperature profile
3. **Sources of waste heat**
   a) Level of heat
   b) System with heat available
4. **Alternate fuel sources**
   a) ADG
   b) Gasification
   c) Exhaust gas
5. **Commercialization Plan / Market analysis**
   a) Demonstration site
   b) Near term markets
   c) Long term

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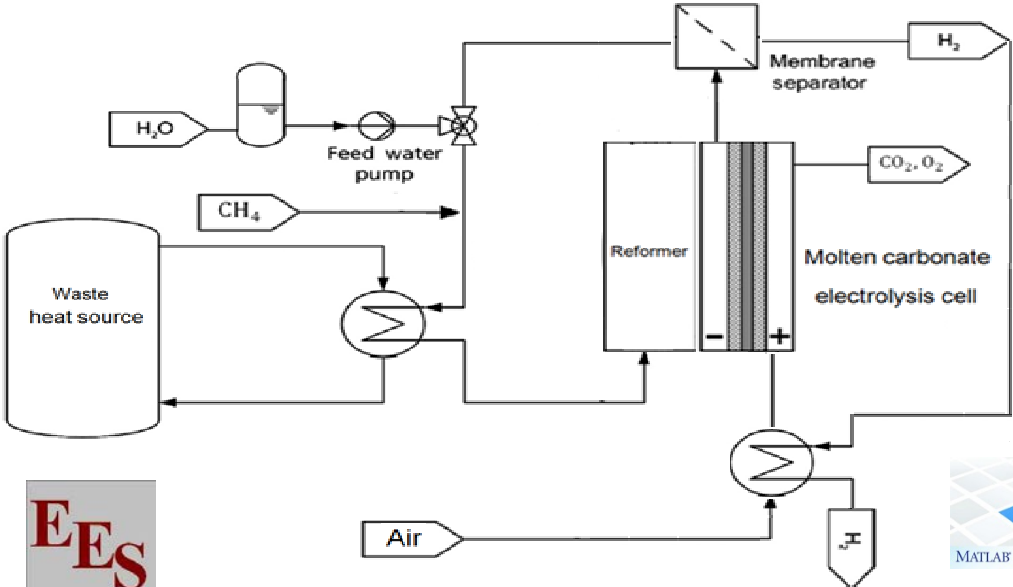
Model for Economics & Optimization

Detailed REP cycle & stack models have been developed



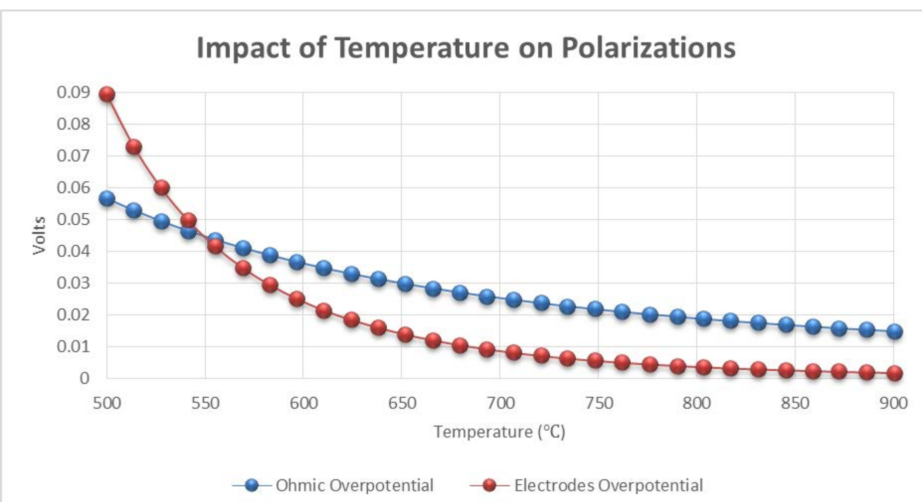
$$\varepsilon_{MCEC} = \frac{\dot{n}_{H_2,Elect} \times LHV_{H_2}}{P_{Elect} + Q_{heat}}$$

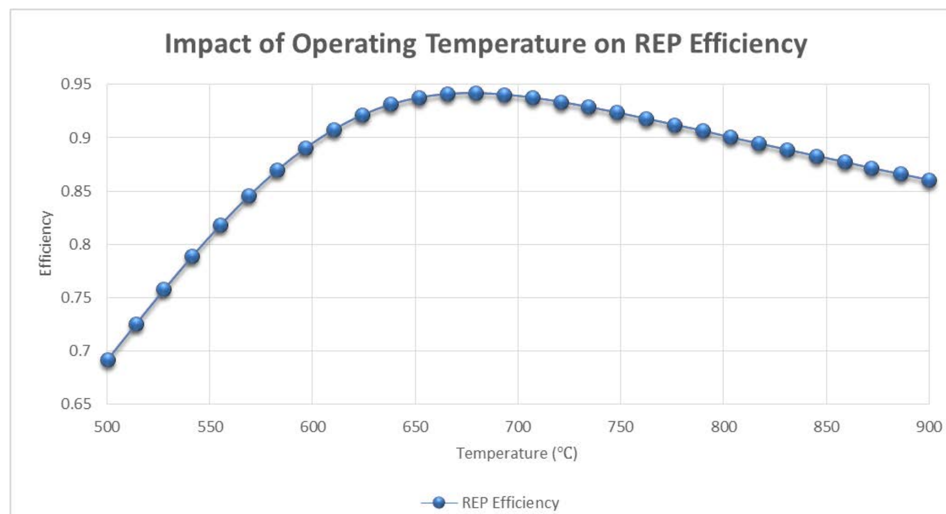
$$\varepsilon_{REP} = \varepsilon_{MCEC}\,\varepsilon_{reformer}$$

$$\varepsilon_{reformer} = \frac{\dot{n}_{H_2,Reform} \times LHV_{H_2}}{\dot{n}_{CH_4,Reform} \times LHV_{CH_4} + Q_{reformer}}$$

EES

MATLAB

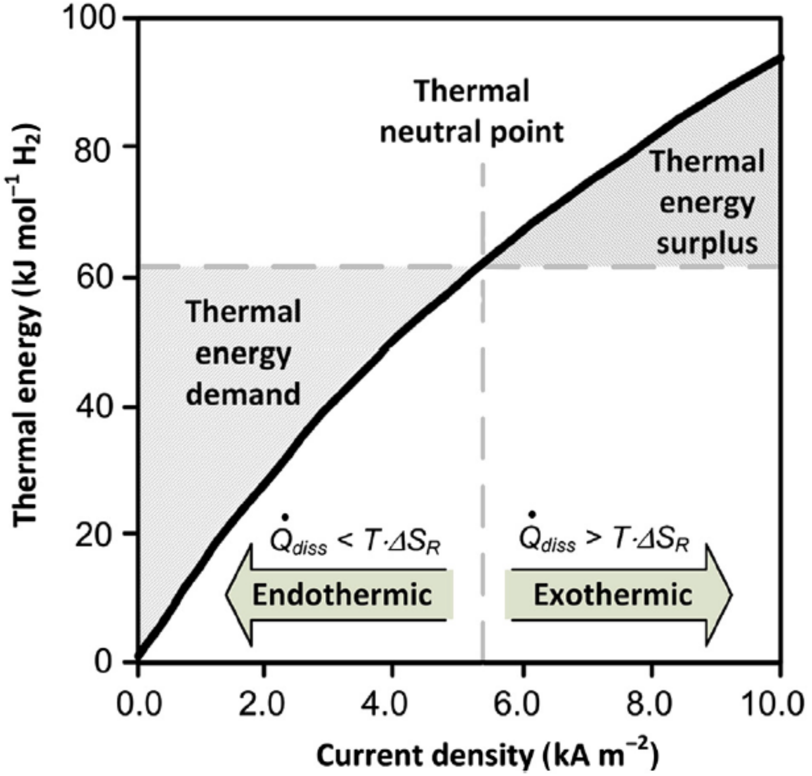




Model for Economics & Optimization

Use model to evaluate external sources of heat, e.g.,

- DFC®
- Gas turbine
- Engine
- Low pressure steam
- Solar w/ electrical backup
- Off-Peak power
- Nuclear
- Heat treating / Sintering
- Glass manufacturing
- Furnaces
- Steel Mills
- Boilers



Look for synergistic hydrogen use opportunities
Evaluate parameters: (1) temperature, (2) hydrogen use, (3) syngas availability, (4) steam availability, (5) other

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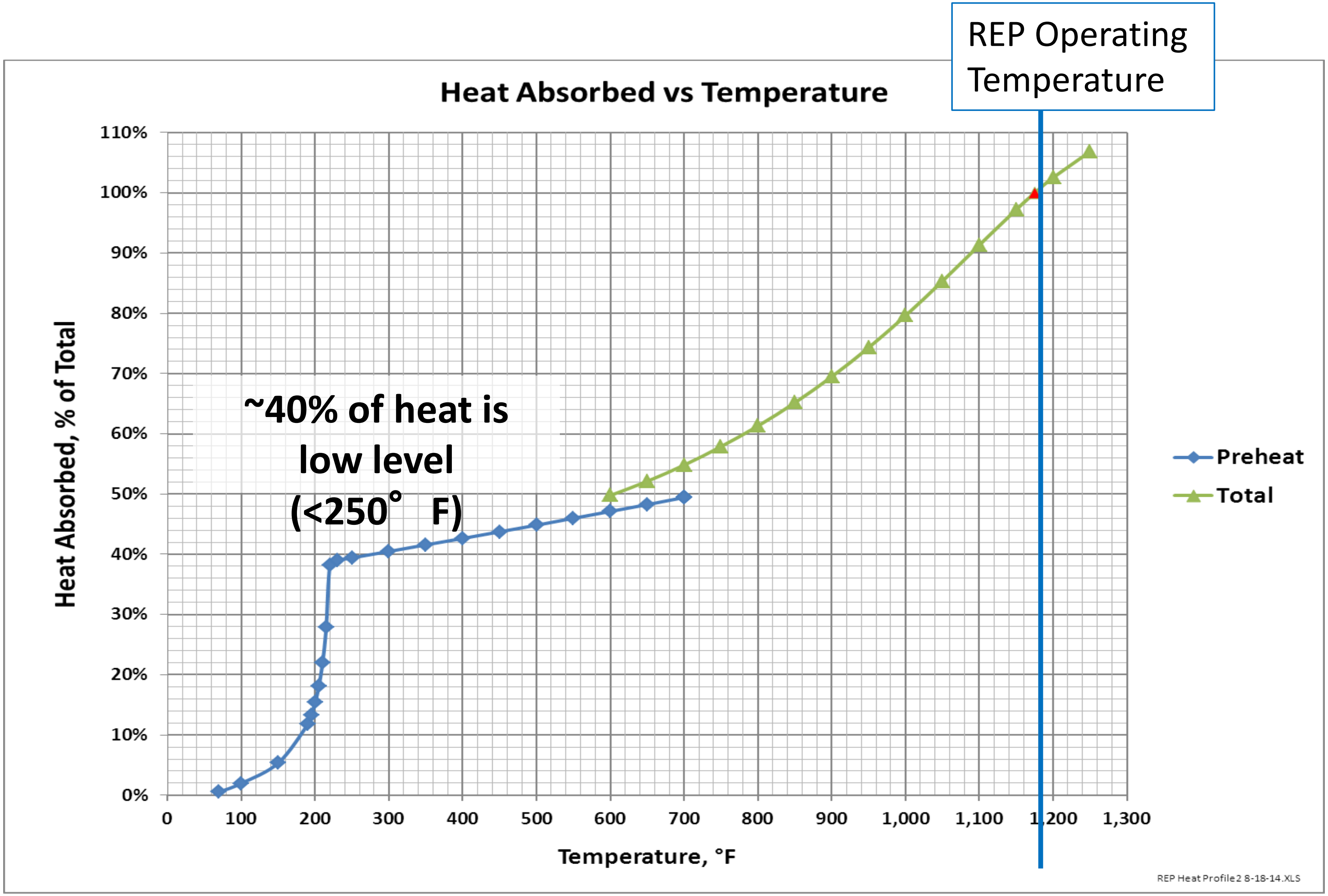
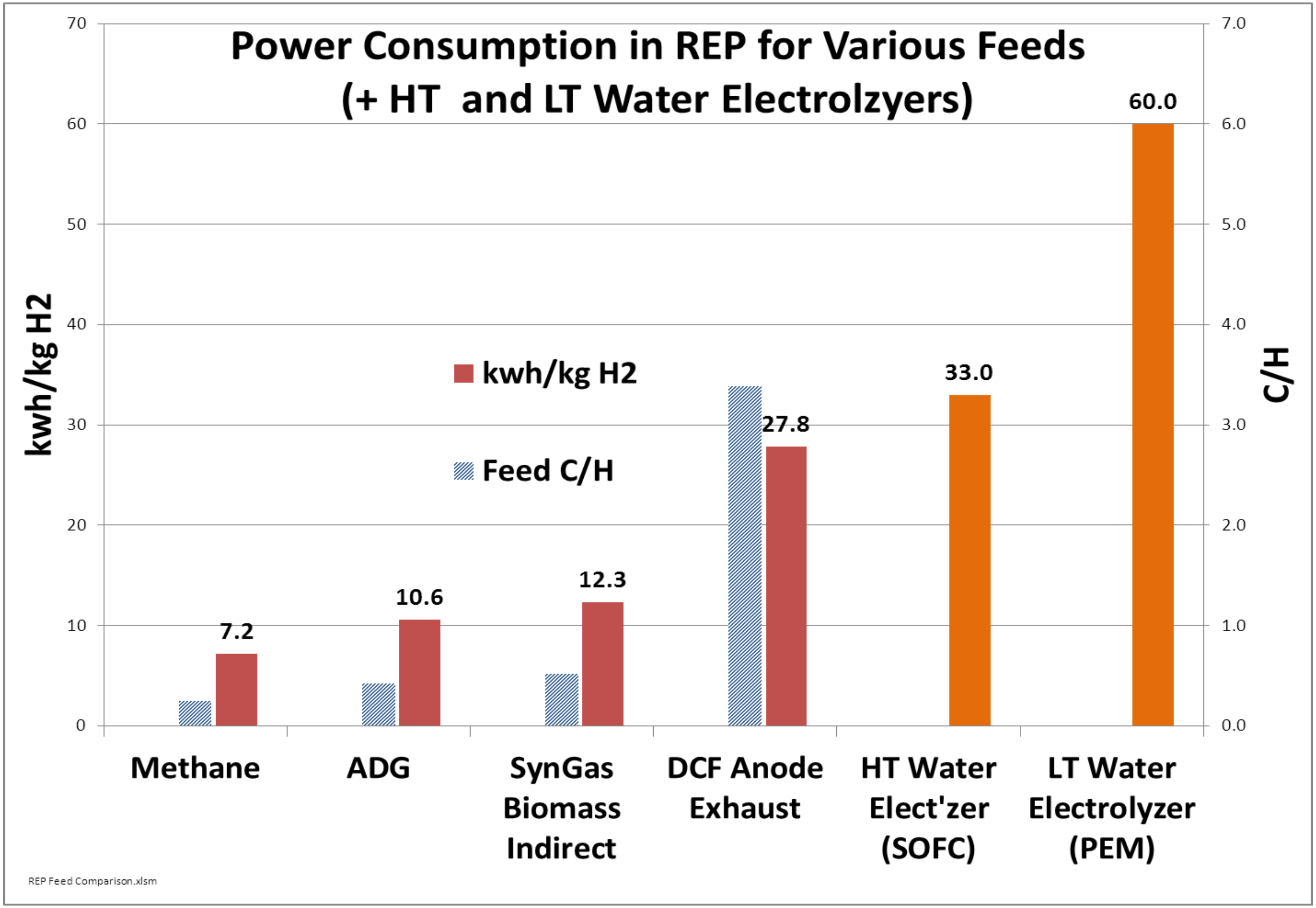
Heat Level Required



Broad Feedstock Options



Initial REP H2A Model

Currently updating using recent cell results.

H2A REP Results	Integrated 1826 kg/d		Stand alone	
Cost Component	Cost Contribution ($/kg)	Percentage of H2 Cost	Cost Contribution ($/kg)	Percentage of H2 Cost
Capital Costs	$0.34	24.3%	$0.93	42.6%
Decommissioning Costs	$0.01	0.9%	$0.04	1.6%
Fixed O&M	$0.12	8.6%	$0.21	9.5%
Feedstock Costs	$0.91	66.0%	$1.01	46.2%
Other Raw Material Costs	$0.00	0.0%	$0.00	0.0%
Byproduct Credits	$0.00	0.0%	$0.00	0.0%
Other Variable Costs (including utilities)	$0.00	0.3%	$0.00	0.2%
Total	**$1.38**		**$2.18**	

Adding polisher in future

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Future Work Plan

1. Longer term stability data
2. Parametric analysis using H2A model
3. Post test analysis of single cell
4. Multi-cell stack design based on single cell data and H2A Analysis
5. Stack test plan
6. Stack fabrication
7. Test facility readiness for multi-cell stack testing
8. Validation testing of the stack
9. Update H2A model analysis based on stack test data
10. Identify potential field site for demonstration
11. Presentation to stakeholders (HPTT, California CEC)

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Technology Transfer Activities

1. **Identified stakeholders from HPTT and California Hydrogen Business Council and UCI meetings**
2. **Initiated development of users workshop in California (UCI leading)**
3. **Presentation to DOE/HPTT in August and March**
4. **Discussions with NREL H2 production group at ESIF**
5. **Patent application filed 2014**

Summary

1. Single Cell performance test results excellent - remain similar to expected performance.
2. Accurate model REP developed - similar to detailed fuel cell performance model.
3. Life of REP cell good to date. Expect good cell life
4. Simulation models (ChemCad) developed to confirm high efficiency, low emissions and potential for low cost
5. Optimizing system to determine best economic cases
   a) Integrated with DFC
   b) Standalone system
   c) Alternate feedstocks (gasifier, ADG, waste gas)
6. System has great potential for alternate uses such as renewable energy storage, chemicals production, or CO2 capture.