FuelCell Energy

Reformer-Electrolyzer-Purifier (REP)

for Production of Hydrogen [CO2 Pump]

2016 AMR (Annual Merit Review), Washington DC

P.I. / Presenter -- Fred Jahnke (fjahnke@fce.com)

FuelCell Energy, Inc.

June 8, 2016

Project ID #: PD112

Ultra-Clean, Efficient, Reliable Power

Overview

Timeline

- Start: October 2014
- End: September 2016

Budget

- Total Budget: $1,250,509
  - Total Recipient Share: $254,215
  - Total Federal Share: $996,294
- Expended to Date*: $1,147,000
  - Total Recipient Share: $233,000
  - Total Federal Share: $914,000

*as of 4/30/16 + committed funds

Barriers

Barriers to hydrogen infrastructure:

- High cost
  - Transportation costs high
  - Limited areas of production
- Emissions limit potential sites
- Scalability of production to local demand

Funded Partners

- UC Irvine National Fuel Cell Center

Impact of REP Technology

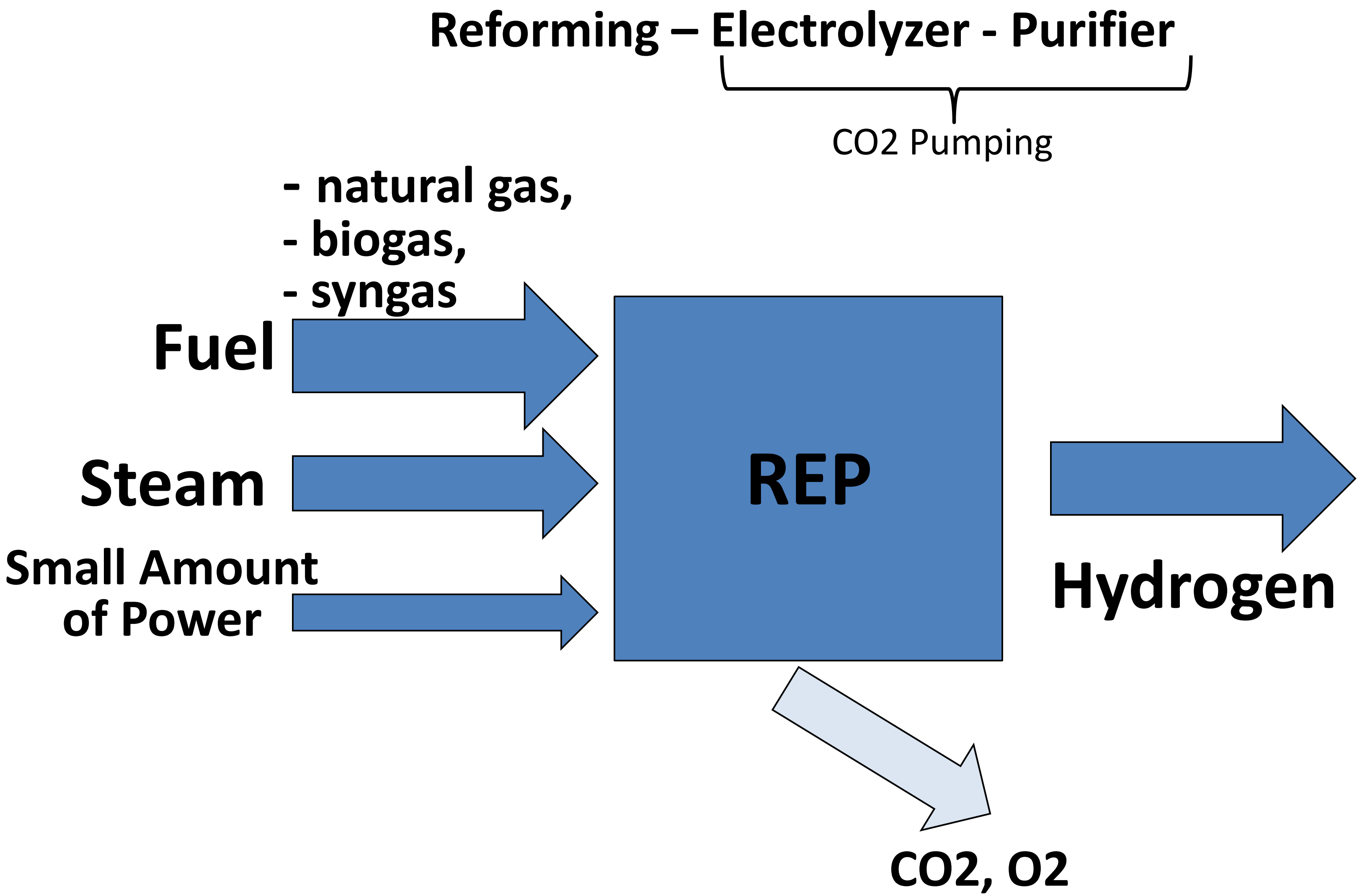
1. Lower cost hydrogen
   - Can meet DOE Targets - Long term H2 less than 2 $/kg
2. Low carbon emissions
   - Can meet DOE Targets - CO2 emissions less than 5,000 g/gge (< 50% typ SMR)
   - System utilizes waste heat
   - 100% conversion of CH4 with recycle
   - Low power high temperature electrolysis removes CO2
   - 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
  - Other sources of waste heat
  - H2 users, low and high pressure
  - CO2 capture potential, Power storage

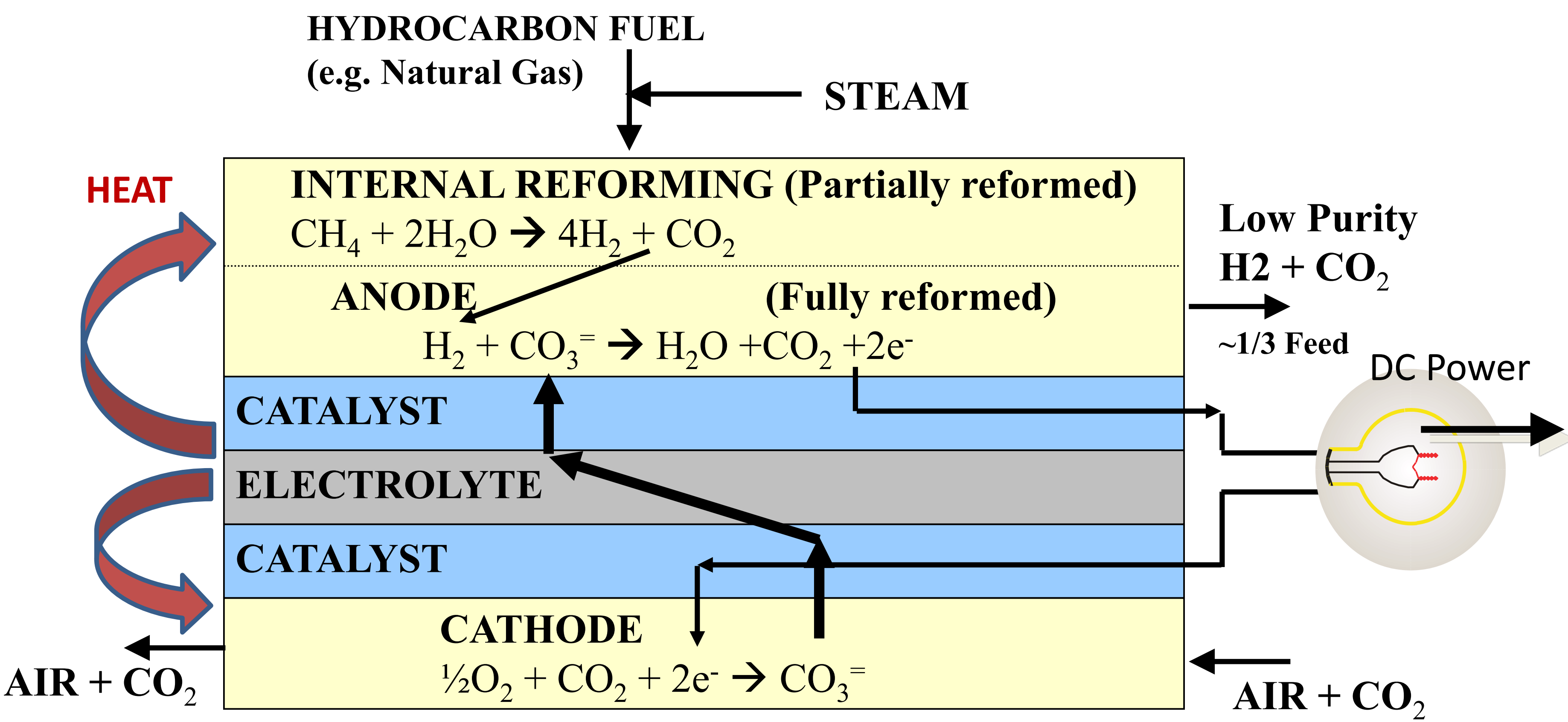
FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

REP Basic Operation



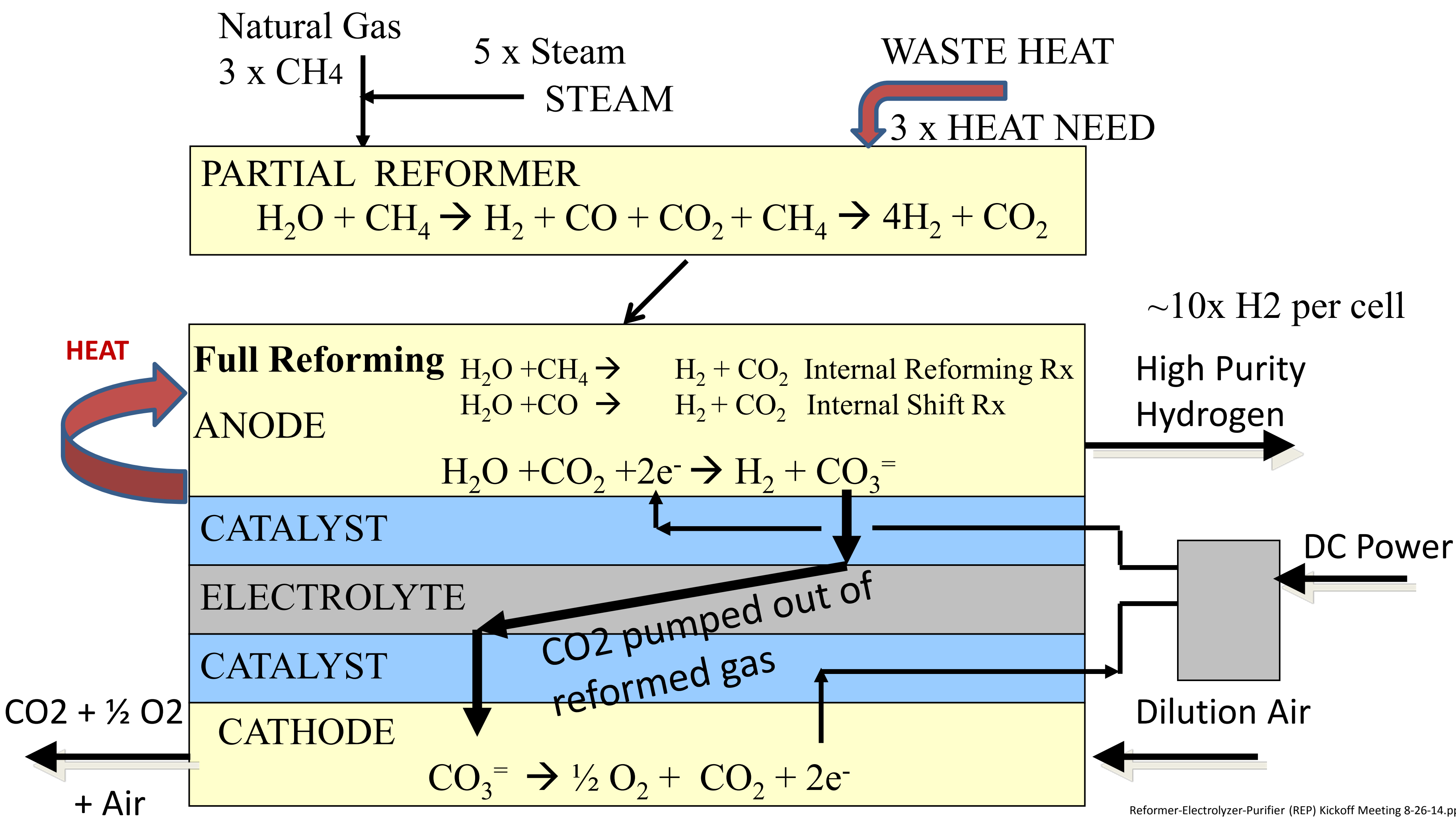
Potential Solution for California Hydrogen Infrastructure

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

Challenges Faced

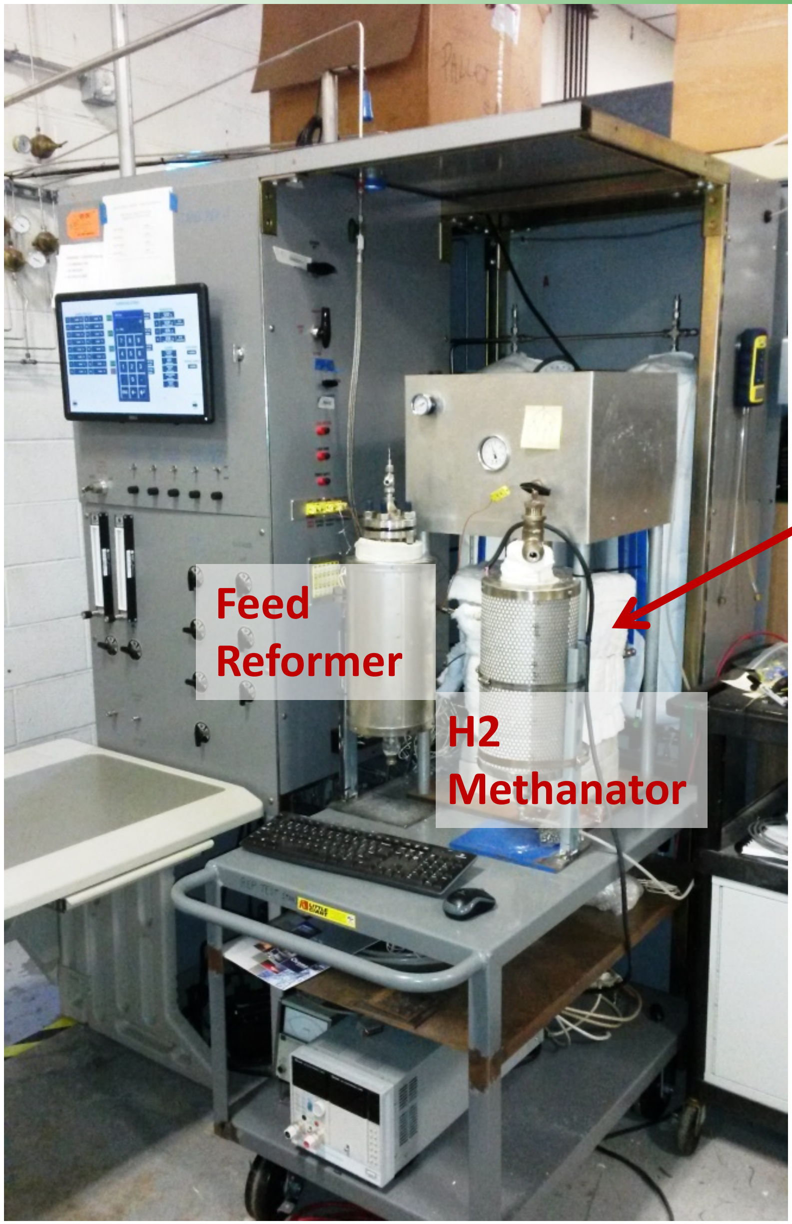
1. First of kind system
   a) Control of system
   b) Safe operation
   c) Test facility limitations
2. Change in operating conditions compared to DFC®
   a) 3 x more feed
   b) 5 x more steam
   c) Pre-reforming of feed gas
3. Safe venting of product H2
4. High ampere power supply

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

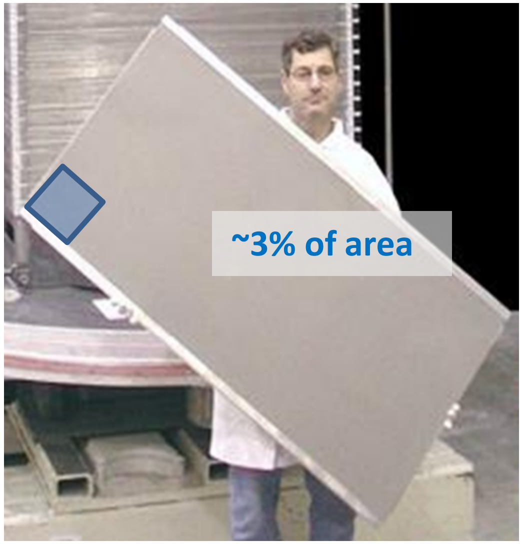
Accomplishments

1. **Single Cell Performance**
   a) Performance matched expectations
   b) Detailed model developed based on data
2. **Life of fuel cell (based on single cell)**
   a) Over 4,000 hours of operation
   b) Test halted due to power and feed interruptions
   c) Degradation rate target achieved
   d) 2 – 5 yr stack projected life
3. **Full Scale Cells Stack Test**
   a) 30 Cell stack built and tested
   b) Testing produced 97-98% H2 @100 kg/d, matched model
   c) Good thermal profile generated
4. **Analyzed system options (continuing)**

REP Single Cell Test Facility

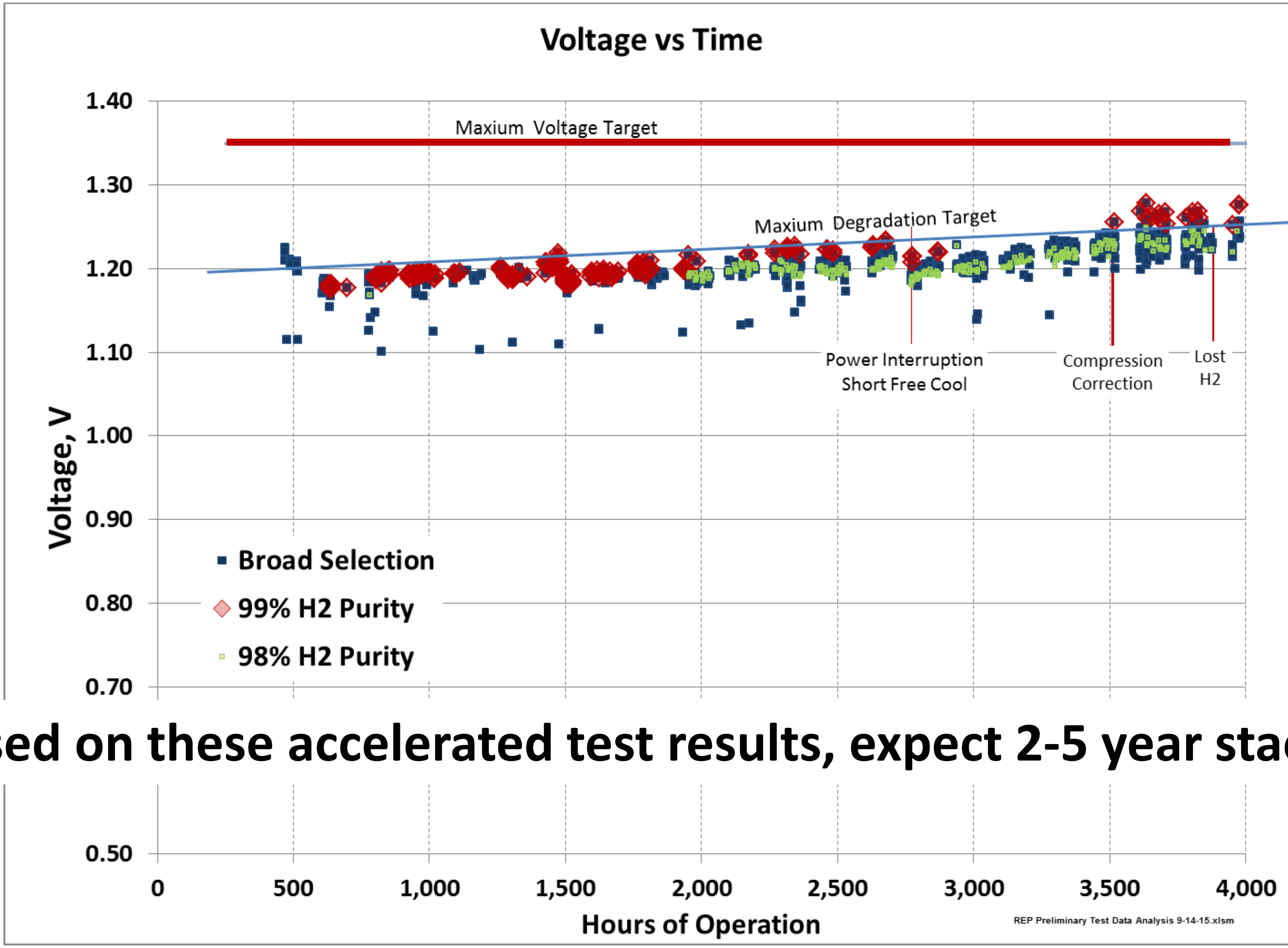


0.15 kg/d



FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Stable Operation over Long Term

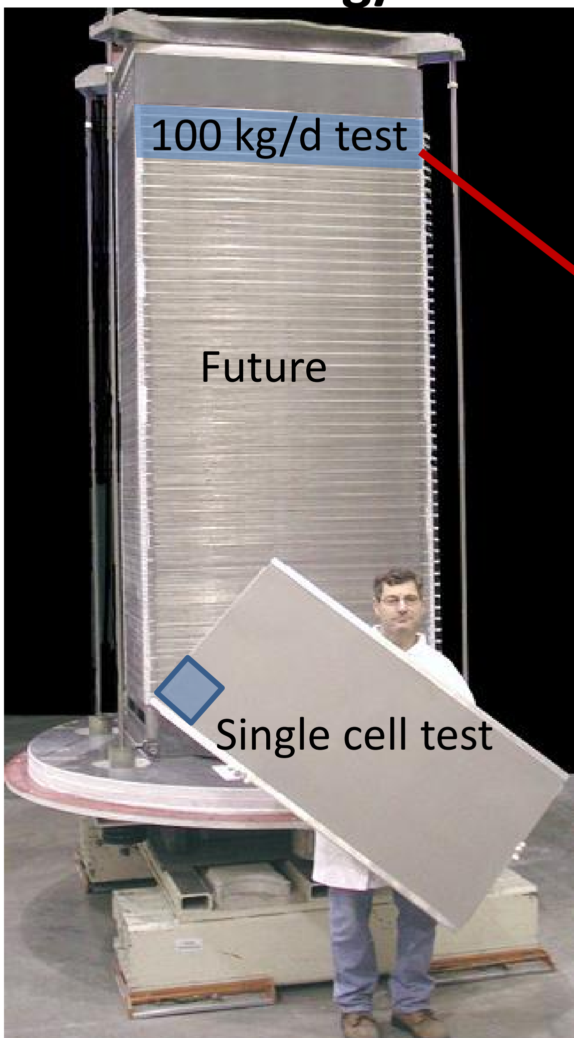


Based on these accelerated test results, expect 2-5 year stack life.

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

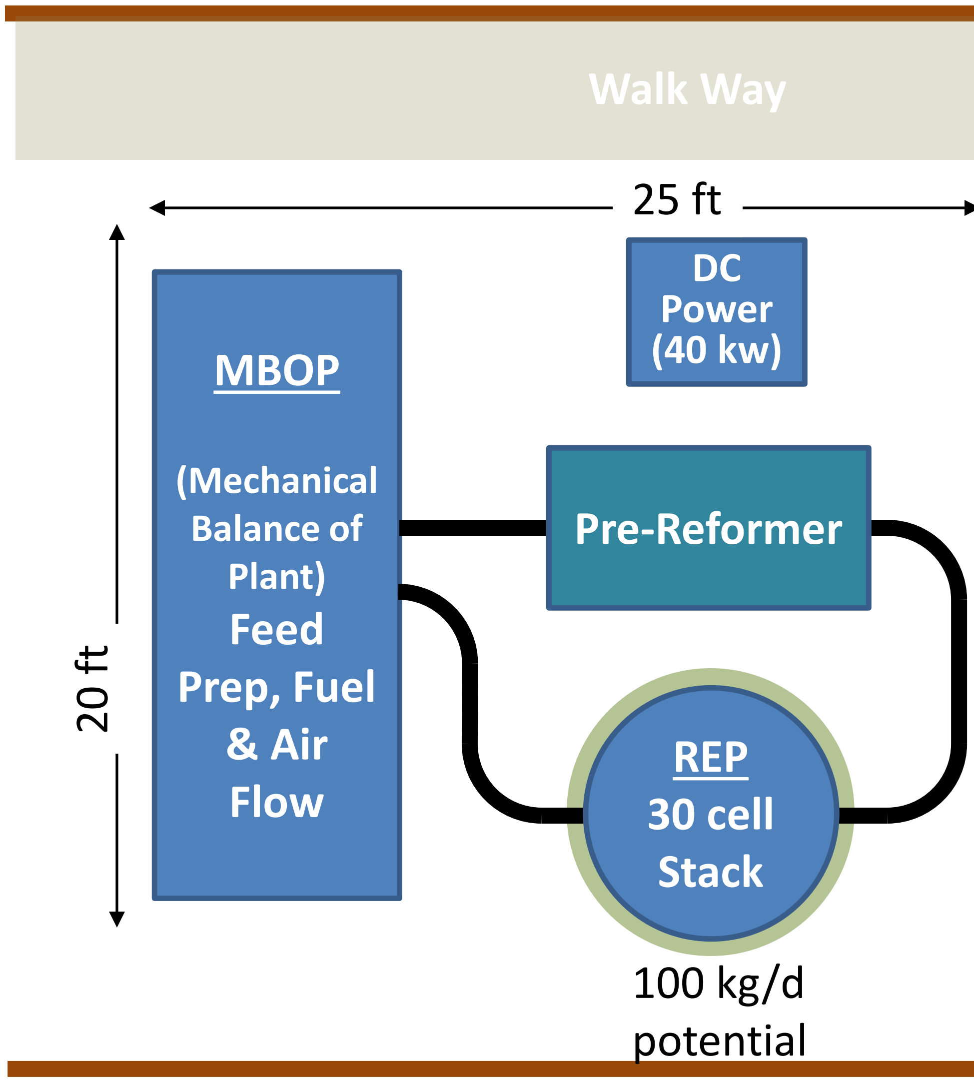
REP Stack Testing

2000 kg/d



100 kg/d

Preparing for Full Load Test



Using existing DFC equipment for testing

Same Equipment as needed for Standalone REP Demonstration

In Large Scale Test Facilities
Stack Test

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Stack Full Load Test, NG Feed

	Target	Design	Test Results	
Amps		1040	950	
Volts/cell	<1.35	1.21	1.22	Meets Target
H2 Purity	>95%	97.4	97.5	Meets Target
Kwh/kg	<8	7.4	7.6	Meets Target
Kg/day	~100	123	110	Meets Target
CO2,g/gge	~5,500	4,900	4,700	

REP 30 Cell 400kw HMB MixedGases 3-31-16ad.xlsm
REP 30 Cell 400kw 950A 20H2 N2 HMB MixedGases 4-29-16.xlsm

Large Scale REP stack proven to be capable of 97%+ pure H2 production with low power input

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Stack Full Load , Anode Exhaust Feed

	Target	Design	Test Results
Amps		1040	1025
Volts/cell	<1.35	1.24	1.19
H2 Purity	>95%	97.7	98.3
Kwh/kg	---	28.1	27.4
Kg/day	---	33	32

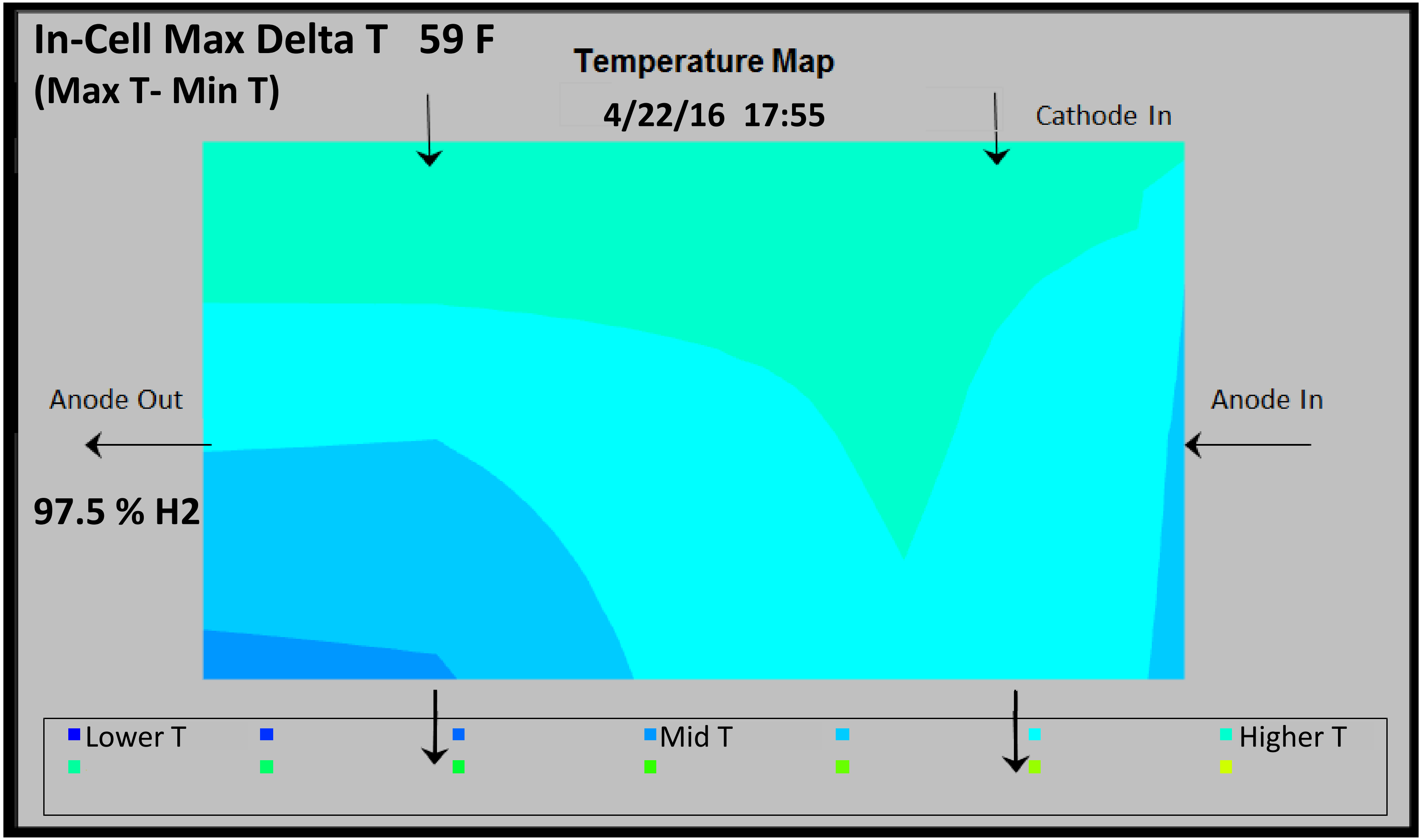
CO2 Free* H2 production

Unit performs as expected with major feed variation

***Only CO2 emitted is CO2 from power production**

Stack Test Temperature Profile

- **Excellent temperature profile at full load**
- **Currently using to confirm modeling**



System Analysis

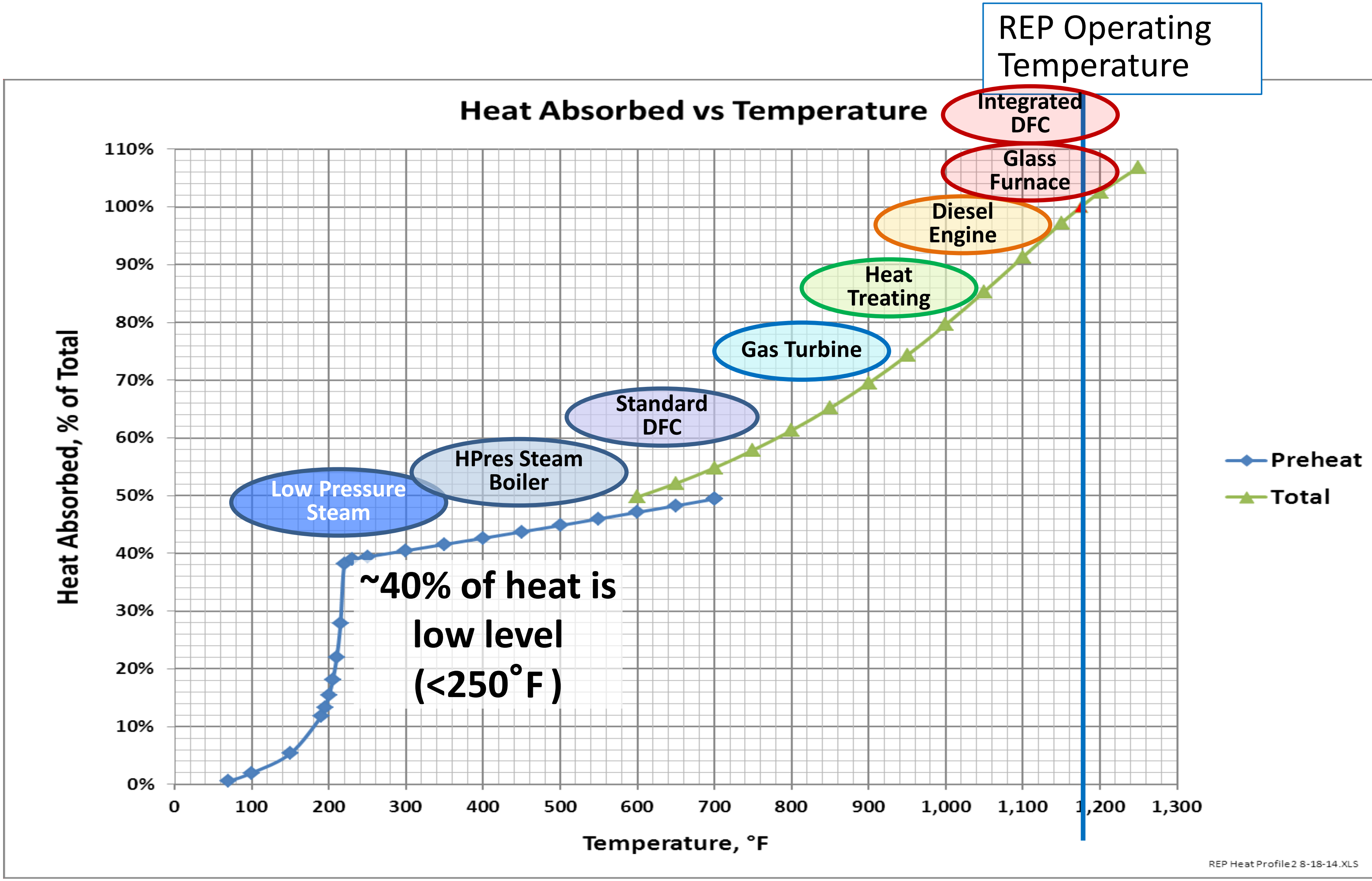
Case	mmbtu NG /kg	Kw NG /Kw H2	REP Power, kwh/kg	H2 Purity, %	Water, kg/kg	Operating Costs, $/kg[1]	CO2, g/gge[2]
1. Base Case - Integrated with DFC	0.069	0.62	7.915	97%	9.3	0.925	4,529
2. Standalone - Grid Powered	0.114	1.02	7.216	98%	9.3	1.188	6,619
3. Standalone - Ext LP Steam	0.095	0.84	7.211	97%	9.3	1.058	5,590
4. Standalone - Self Powered	0.138	1.23	0.000	97%	9.3	0.488	8,082
5. Standalone - Syngas Grid	0.066	0.59	12.181	98%	8.7	1.529	0[6]
6. Int with DFC - AE Pwr Storage	0.010	0.09	29.518	98%	9.2	1.886	0[4]
7. Int with SOFC - AE Pwr Storage	0.000	0.00	23.768	97%	0[3]	1.529	0[4,5]
8. Standalone - ADG Feed	0.104	0.93	10.277	98%	9.3	1.296	0[6]

REP Cases HMB Summary R5.xlsm

[1] Assumes $6.77/mmbtu NG (LHV), $0.057/kwh power.
[2] Does not include CO2 associated with power used.
[3] All water needed is already in SOFC anode exhaust
[4] No additional CO2 emitted other than CO2 from power production
[5] Potential CO2 capture for zero CO2 power from NG as well as H2
[6] Renewable Hydrocarbon Feed

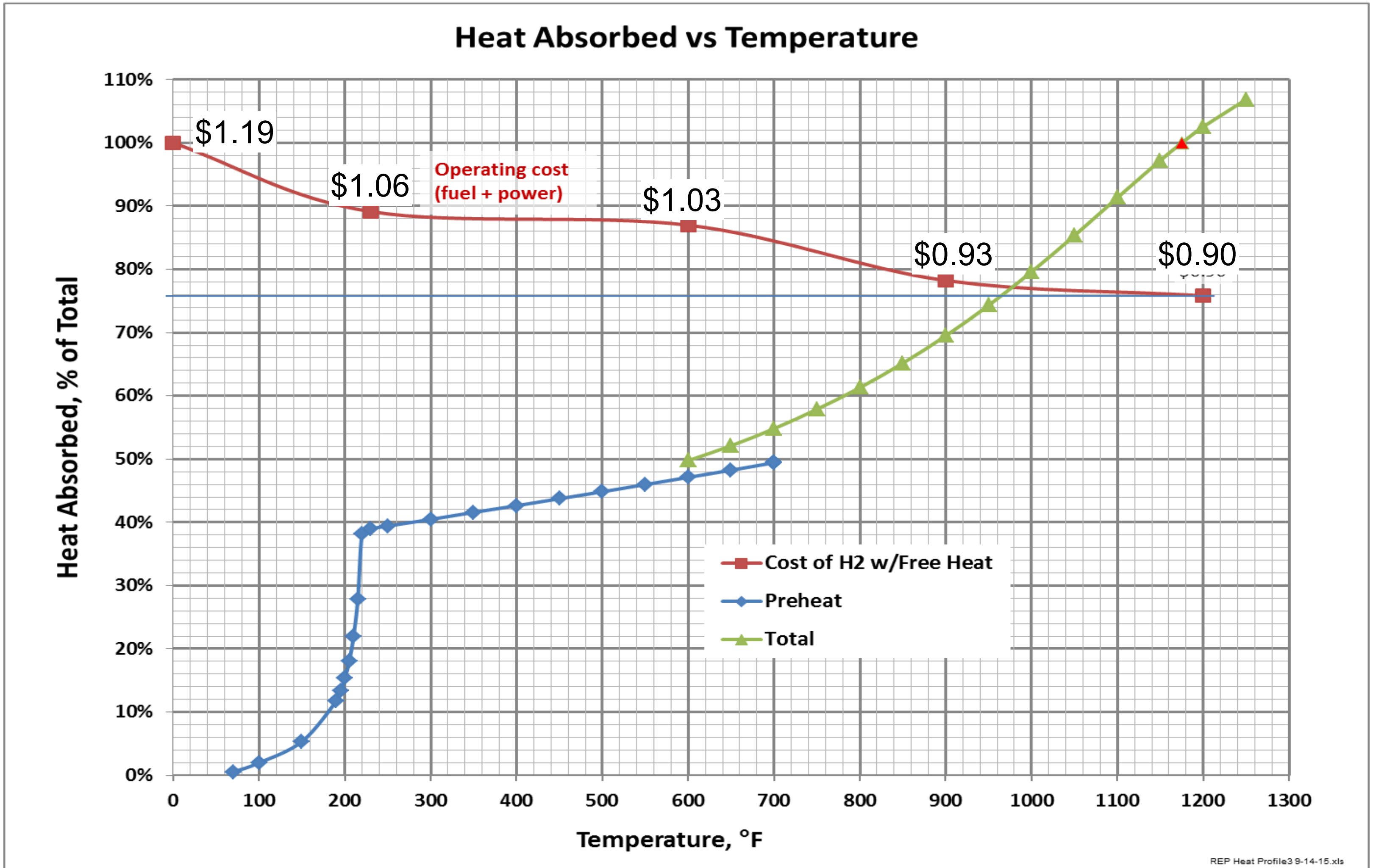
Sources of Waste Heat

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power



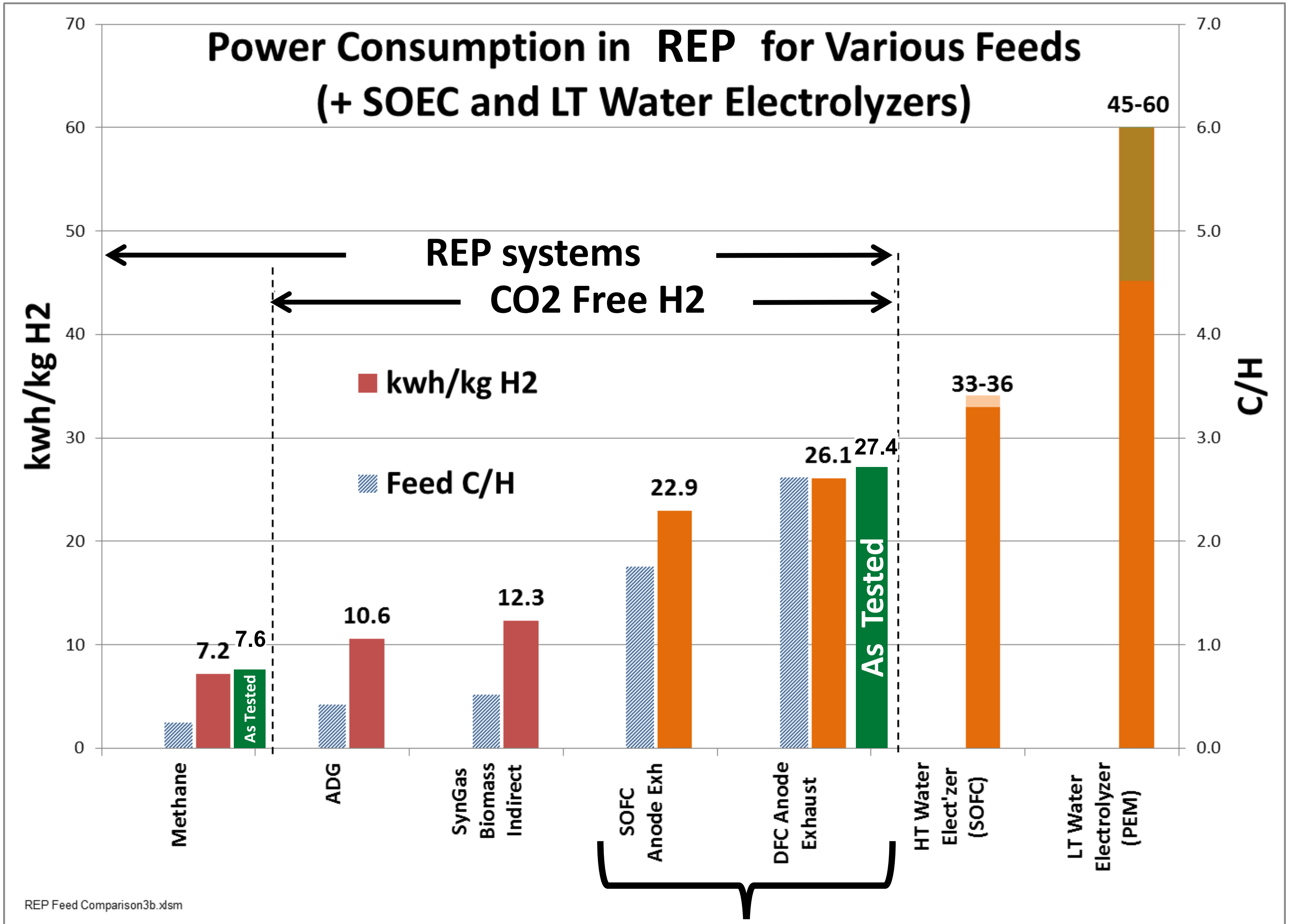
FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Impact of "Free" Waste Heat on Op Cost



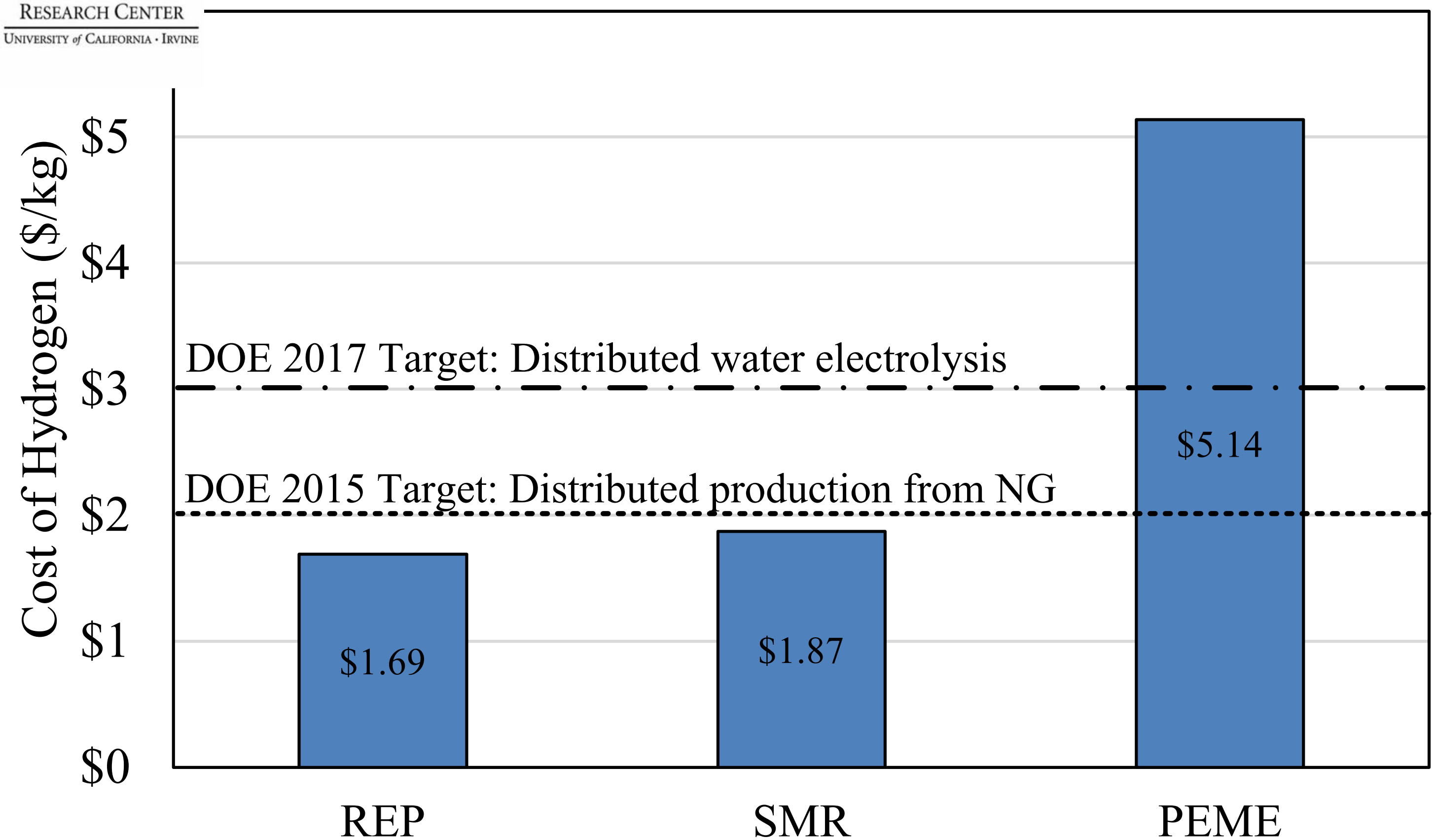
"Free" waste heat reduces cost of H2 $0.29/kg, low level $0.13/kg

Impact of Different Feeds



Lowest Cost with off peak power

UCI Economic Analysis using H2A

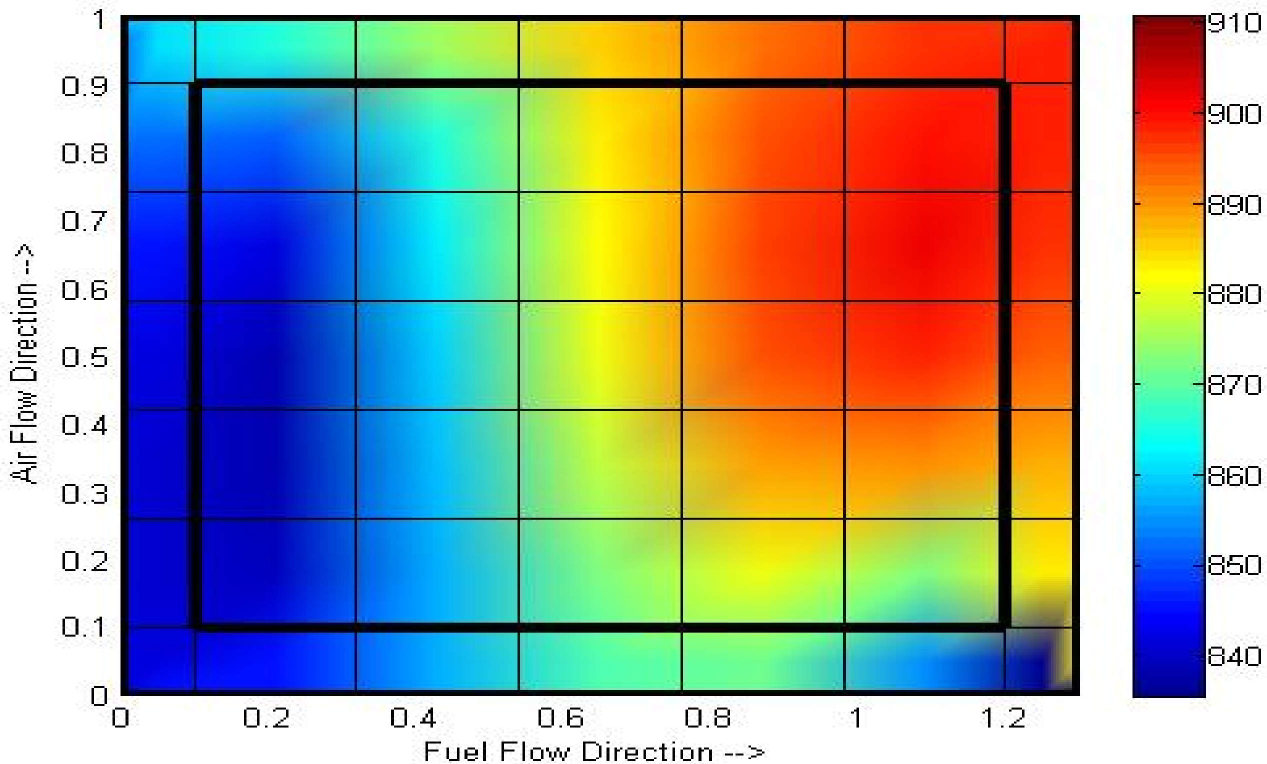


Hydrogen[(1)] production cost in a 1500 kg/day design capacity forecourt station with various production technologies
(ECS Trans. 2016 71(1): 179-192)

(1) based on 99.995% H2 at 300 psig for all cases

UCI Model Predictions

Temperature profile generated from a quasi-3D MCFC dynamic model
Developing the MCEC model and verify with the experiment measurement



Cross-flow configuration steady-state temperature profile, Uf=65%

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

Technology Transfer Activities

1. Presentation to DOE/HPTT
2. Presentation at Fuel Cell Seminar
3. Continuing to identify stakeholders from HPTT, California Hydrogen Business Council, UCI and other meetings
4. Initiating development of users workshop in California (UCI leading)
5. Patent application filed 2014, additional patents filed 2015, continuing as technology develops
6. Analyzed home refueler opportunity

UCI = University of California, Irvine
HTTP = Hydrogen Production Technology Team

FuelCell Energy
Ultra-Clean, Efficient, Reliable Power

REP Development Summary

1. **Single Cell Performance and Life results excellent**
2. **Accurate model REP developed**
3. **Met Go-NoGo decision, proceeded to 100 kg/d test**
4. **Optimizing system shows great potential for low CO2 emissions**
   a) **Integrated with DFC and SOFC**
   b) **Standalone system / low level heat integration**
   c) **Alternate feedstocks (gasifier, ADG, waste gas)**
   d) **Potential for zero CO2 production of H2**
5. **Initial performance test of short stack (100 kg/d)**
   a) **Excellent at low and full load. Performed as expected**
   b) **No impact of operation in REP mode seen on stack**
      Same power generation performance before and after REP operation

Future Work Plan

1. Continue single cell testing
   a. Feedstock variation (Including ADG, Anode Exhaust)
   b. CO_2/O_2 co-production
2. Analyze 100 kg/d test results
3. Update H2A model analysis based on stack test data
4. Conceptual design of on-site REP system for low cost H_2 refueling
5. Identify potential funding for continuation of 100 kg/d testing (long term testing)
6. Presentation to HPTT stakeholders (in May)
7. Final report

Need longer term full scale stack testing to confirm stack life (not part of initial program)