FuelCell Energy

Electrochemical Hydrogen Compressor

Ludwig Lipp

FuelCell Energy, Inc.

June 10, 2015

Project ID #PD048

Overview

Timeline

- Project Start Date: 7/15/10
- Project End Date: 7/14/15

Budget

Total Project Value: $2,623,213

- Total Recipient Share: $629,571
- Total Federal Share: $1,993,642
- Total DOE Funds Spent*: $1,676,849

*As of 1/31/15

Barriers

- Barriers addressed for gaseous hydrogen compression:
  - More reliable
  - Lower-cost
  - Higher efficiency

Partners

- Collaborations: Sustainable Innovations, LLC
- Project lead: FuelCell Energy

FuelCell Energy

Sustainable Innovations

Relevance

Objective: Develop solid state hydrogen compressor technology for vehicle refueling with greater reliability, scalability and lower costs

Impact of EHC:

- **Increased reliability/availability over current mechanical compressors**
- **Ensures "no possibility of lubricant contamination" (No moving parts) → Fuel cell quality H_2**
- **Increases compression efficiency to 95% (DOE 2015 Target)**
- **Potentially reduces cost of H_2 delivery to <$1/gge (DOE Long Term Target)**

Relevance

EHC Advantages Over Mechanical Compressor for Refueling:

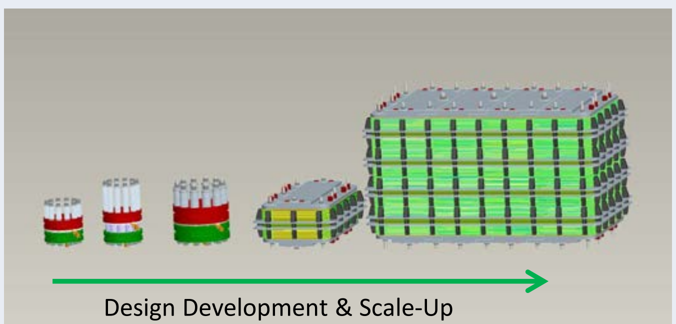
- **Lower maintenance cost: No moving parts, longer MTBF**
- **No noise: Can be permitted in high visibility area**
- **No contaminants added: No lubricants required – maintains ultra-high H_2 purity required by FCV at lower cost**
- **Versatile guard bed for impurities**
- **Robust for fast-fill: No shock and vibration caused by rapid and frequent start-up/shut-down cycles and variable fill rates**
- **Potentially eliminates expensive pre-chilling equipment: Much lower temperature rise during compression**
- **Higher overall efficiency: Efficient under variable operating conditions; efficient at low inlet pressures**
- **Thus lower overall delivered hydrogen cost**

EHC is ideally suited for hydrogen refueling

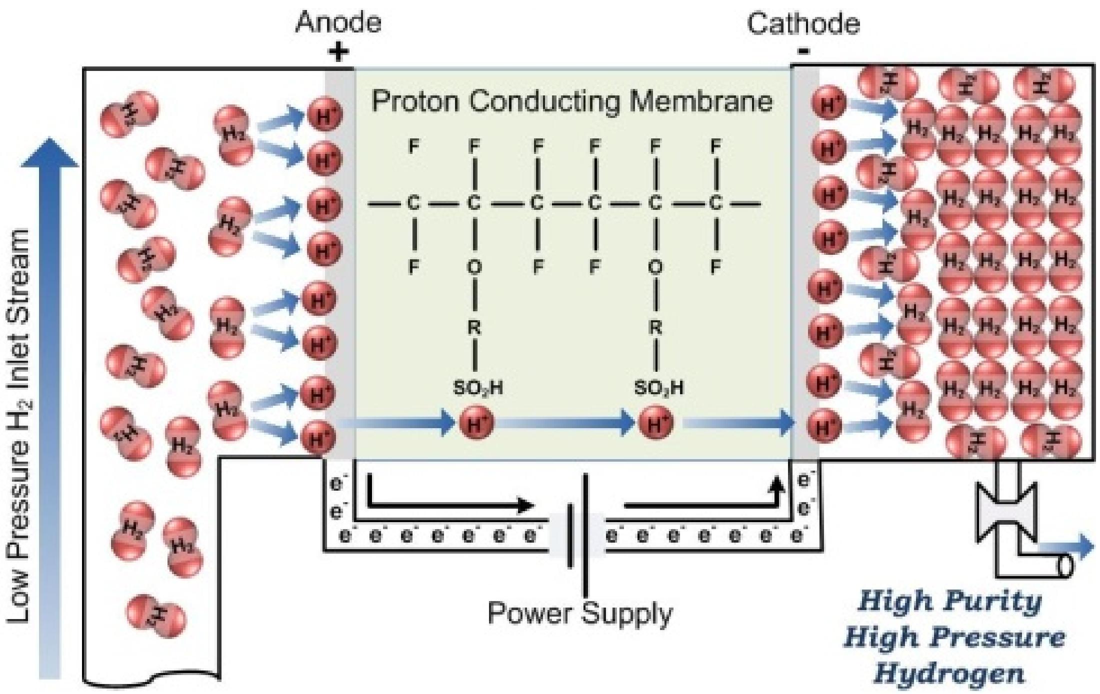
Approach

- **Use high-pressure electrolyzer experience for mechanically robust cell design over a wide range of operating pressures**
- **Multi-cell stack and larger cell area to increase hydrogen compression capacity**
- **Reduce capital and operating costs by higher current density operation with enhanced thermal management**
- **Increase H_2 recovery efficiency by improved fluids management and flowfield design**
- **Reduce capital cost by reducing number of parts per cell**

Approach

ITEM	APPROACH
Increase Pressure, Life, Efficiency	-Cell & Stack Design Enhancements -MEA Improvements
Lower System Cost 	-Thermal Management and Integration -Increase Single-Stage Pressure Capability -Lower Cost Materials of Construction -Lower Part Count -Design for Manufacturing & Assembly -Stack Scale-up -Hybrid Operation

Principle of Electrochemical Hydrogen Compressor



EHC does not follow

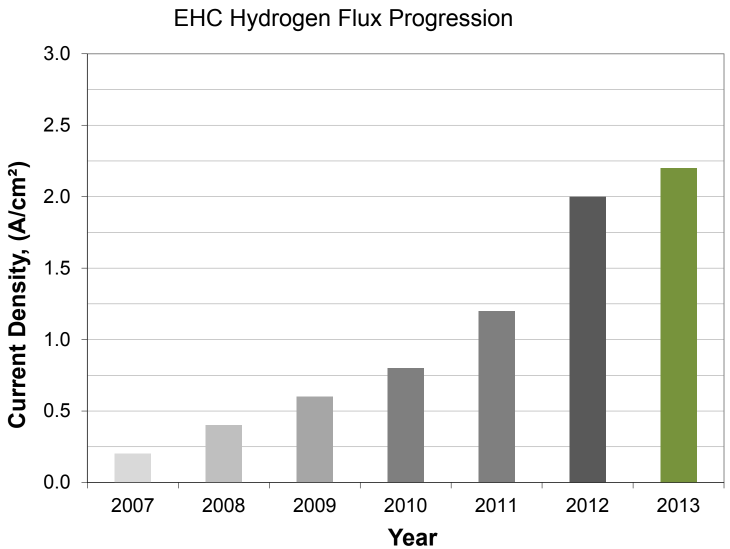
P V = n R T

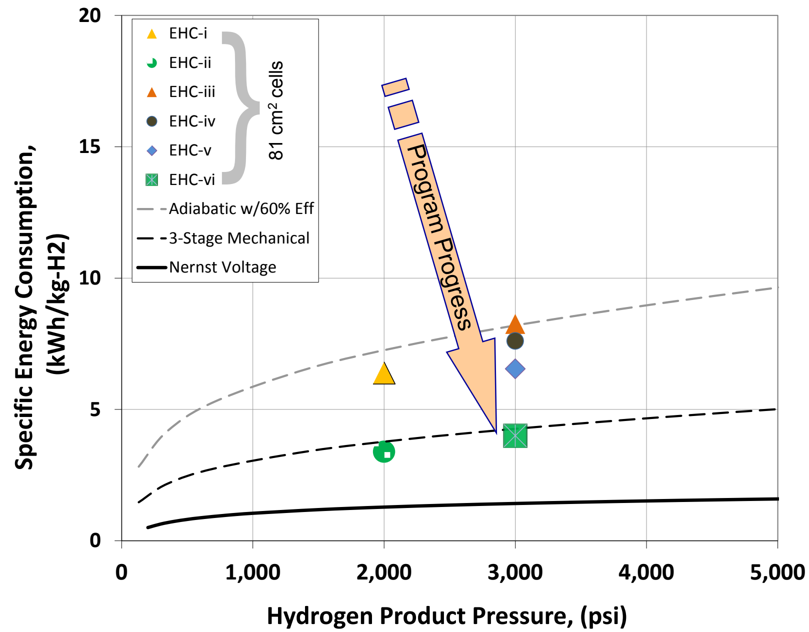
Rather Nernst Eqn:

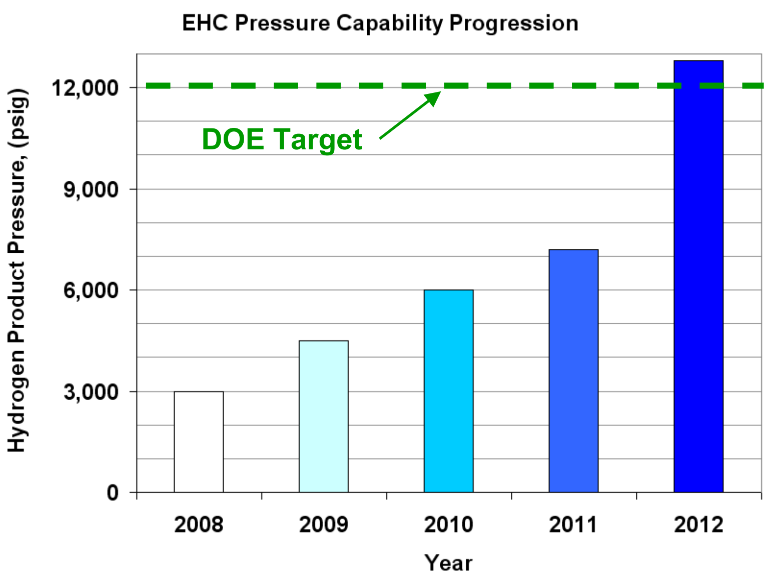
$$V_{theor} = \frac{RT}{nF} \ln\left(\frac{P_2}{P_1}\right)$$

- **Simple operating principle with no moving parts – Solid State !**
- **Use of hydrogen electrode for high compression efficiency**

EHC Single Cell Data







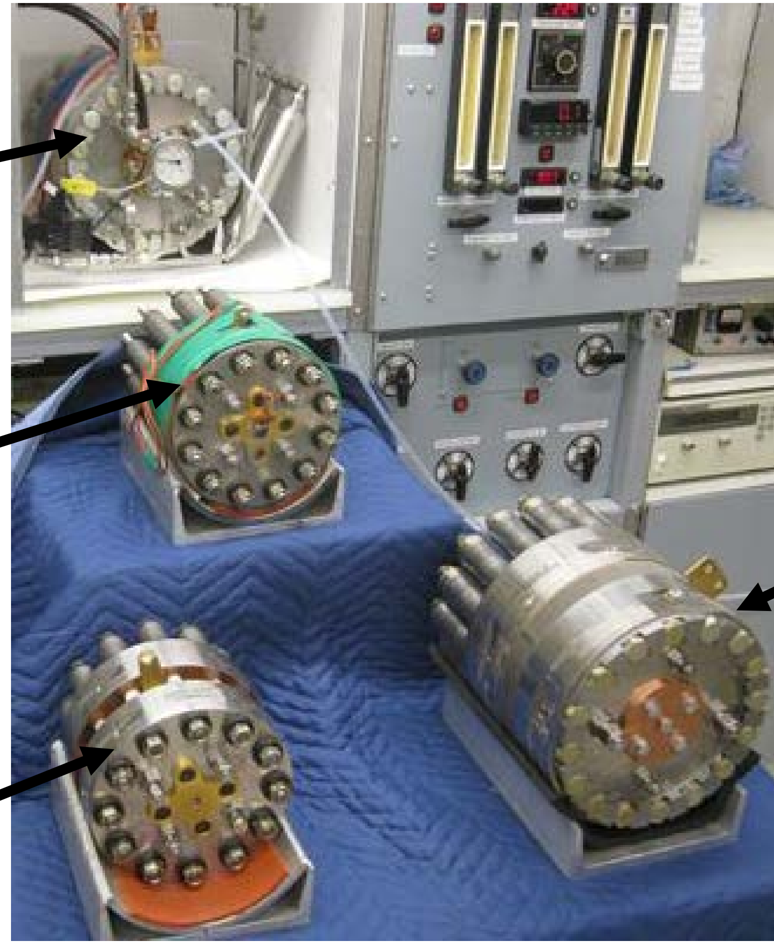
Met DOE 2015 pressure target for small compressors

EHC Durability

0.2 lb/day,
>16,000 hrs,
185 cm^2 cell

0.1 lb/day,
10,000 hrs,
82 cm^2 cell

0.5 lb/day,
3,000 hrs,
5-cell 82 cm^2 stack



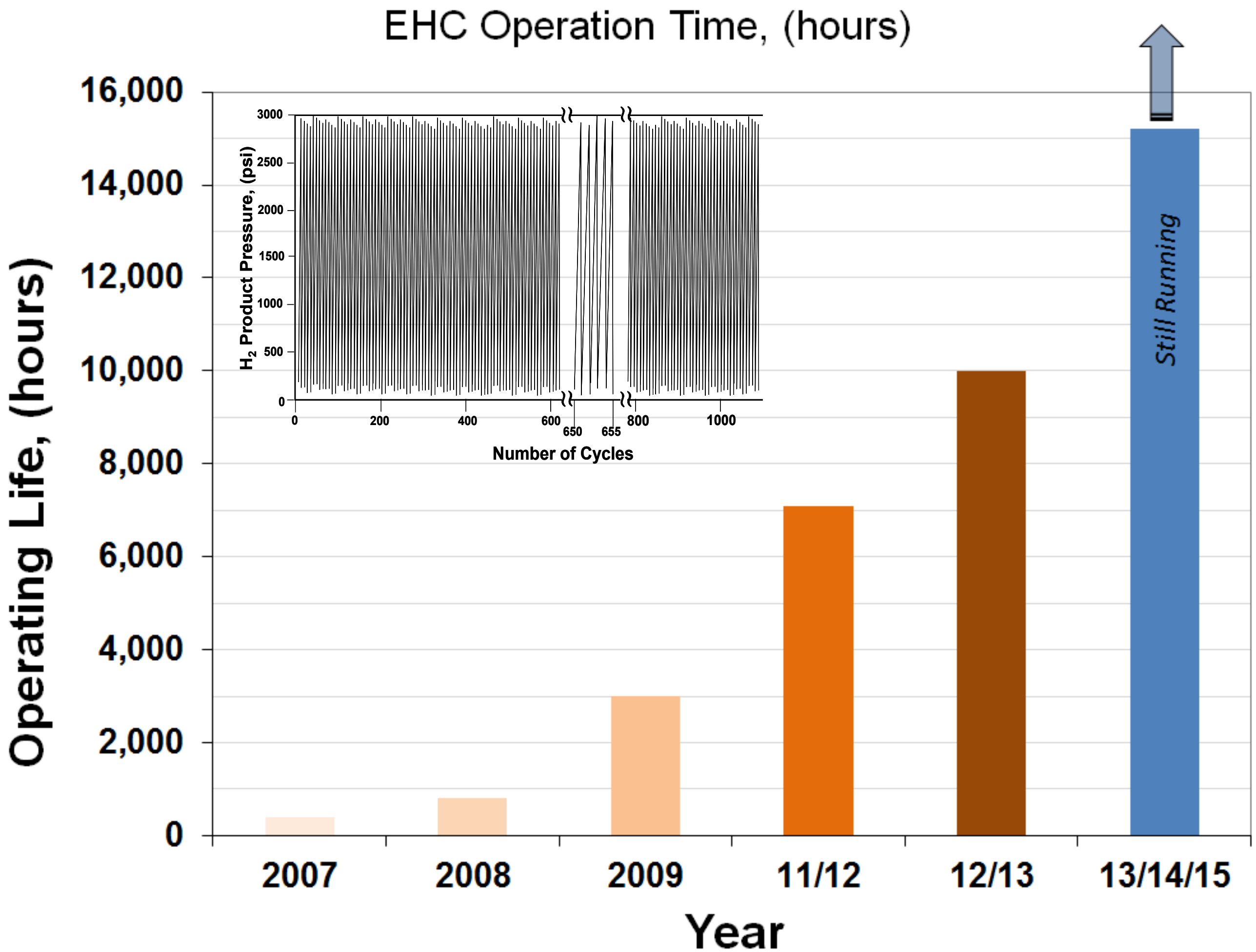
2 lb/day,
>3,000 hrs,
8-cell 185 cm^2 stack

Cumulatively >30,000 hr Cell And Stack Operation

FuelCell Energy

Sustainable Innovations

EHC Durability Improvement



10,000 hrs Operation at ~95% H_2 Recovery in 81 cm^2 Cell

>16,000 hrs at >95% H_2 Recovery in 185 cm^2 Cell

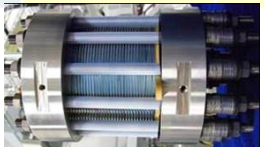
FuelCell Energy

Sustainable Innovations

EHC Stack Development

	3-Cell Stack #1	3-Cell Stack #2	3-Cell Stack #3	5-Cell Stack	10-Cell Stack	8-Cell Stack 185 cm^2	30-Cell Stack 82 cm^2	30-Cell w/fins 82 cm^2
Pressure, (psig)	4,550	Up to 1,000	2-3,000	Up to 3,000	Up to 3,050	3,000	**4,500**	4,500
Current Density, (mA/cm^2)	500	Up to 2,200[&]	500	450	500	500	**200**	400
Capacity, (lbs/day)	0.2	Up to 0.8	0.2	0.3	0.6	2	**1**	2
Operation, (hours)	150	~100	>2,000[†]	1,800	~400	>3,000	**>3,000***	>200[†]

* Currently In Operation at FCE
† At Sustainable Innovations
& Thermal Management needs further improvement

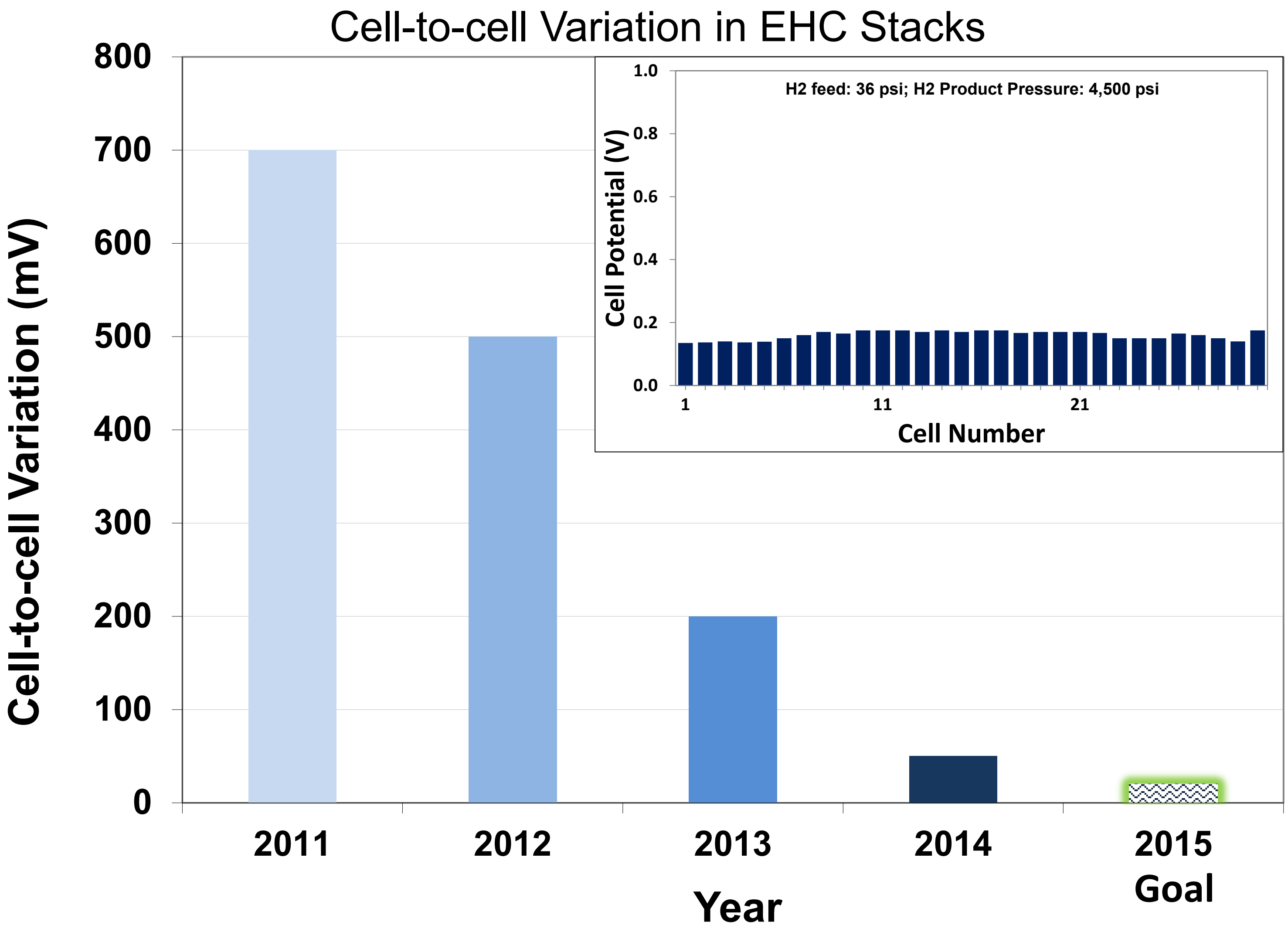


Cumulatively >10,000 hrs of Stack Operating Experience

FuelCell Energy

Sustainable Innovations

Cell-to-Cell Performance Variation



Reduced Cell-to-cell Variation by >70%

FuelCell Energy

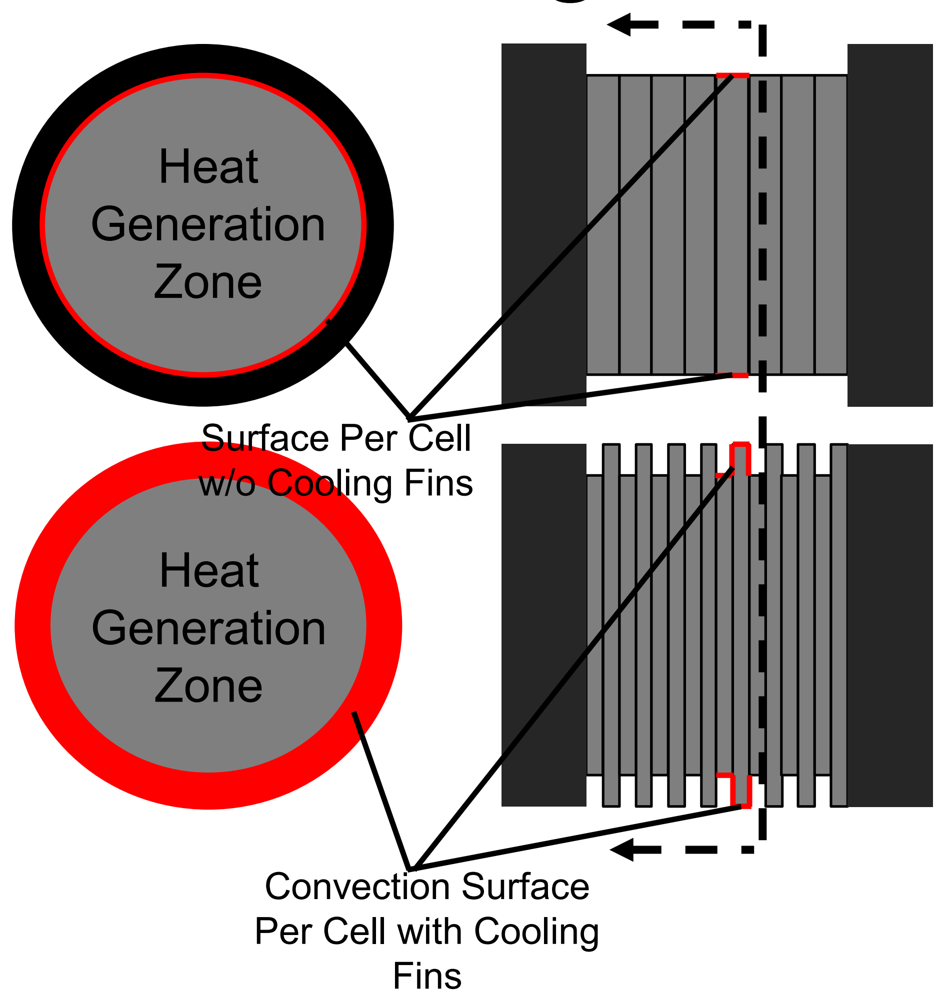
Sustainable Innovations

Thermal Management Options Investigated

- **Liquid Cooling:**
  - **Stable operation demonstrated up to 1,000 mA/cm^2 at 3,000 psi**
  - **Recirculation pump reliability is a concern for long-term operation**
  - **In multi-cell stacks observed higher cell-to-cell performance variation**
- **Gas Phase Cooling:**
  - **Stable operation demonstrated up to 100-400 mA/cm^2 at 4,500 psi**
  - **Simpler and more reliable**
  - **Used heat transfer modeling to increase the current density**

Thermal Management Model* for Stack with Cooling Fins

- Heat loss at endplates is neglected in long stack model case
- Accurate if end plates are insulated to induce temperature uniformity at end cells
- Heat is assumed to be generated uniformly in active area
- Convection coefficient is estimated for free convection
- Dramatic increase in convective surface area with fins addition: from 3 to 50 in^2



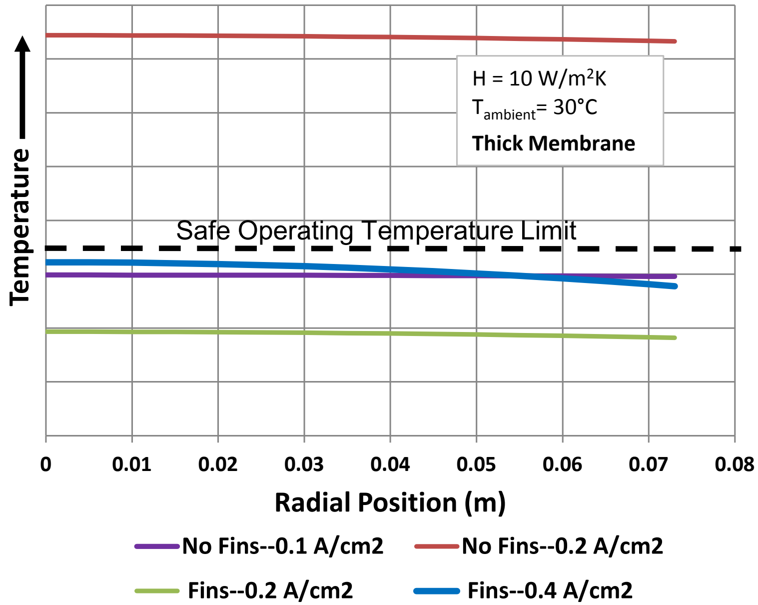
Fins increase heat exchange area by ~20x

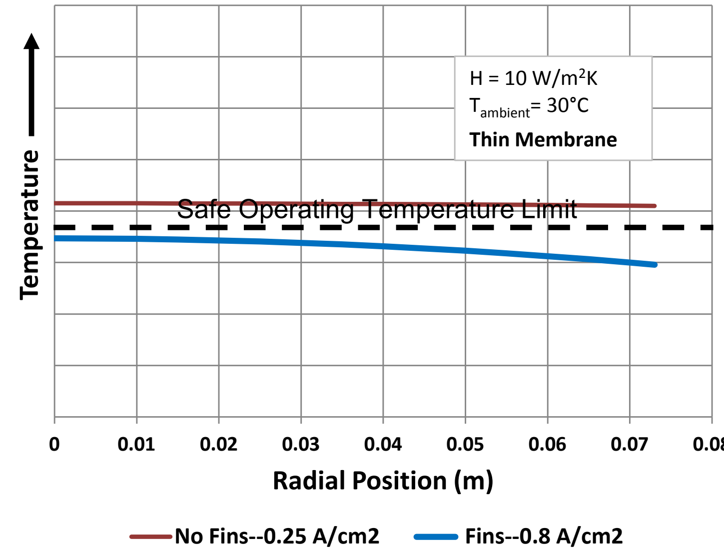
FuelCell Energy

* Developed by Sustainable Innovations for NASA application

Sustainable Innovations

Thermal Modeling Results





- No significant impact on cost
- No increase in envelope dimensions

With thick membrane can increase current density to **400 mA/cm²** = 4x increase compared to no fins

With thin membrane can further increase current density to **800 mA/cm²**

FuelCell Energy

Sustainable Innovations

EHC Capacity Scale-up

Cell area: 82 → 185 cm²
Stack: 1 → 30 cells

0.1 → 2 lb/day
(DOE Program)

1-2 lb/day
30-cell stack

Up to 10 lb/day
(NASA Program – 12 cells of 800 cm² area)

H_2 capacity increased by two orders of magnitude

FuelCell Energy

Sustainable Innovations

EHC Building Block Design for Multiple Applications

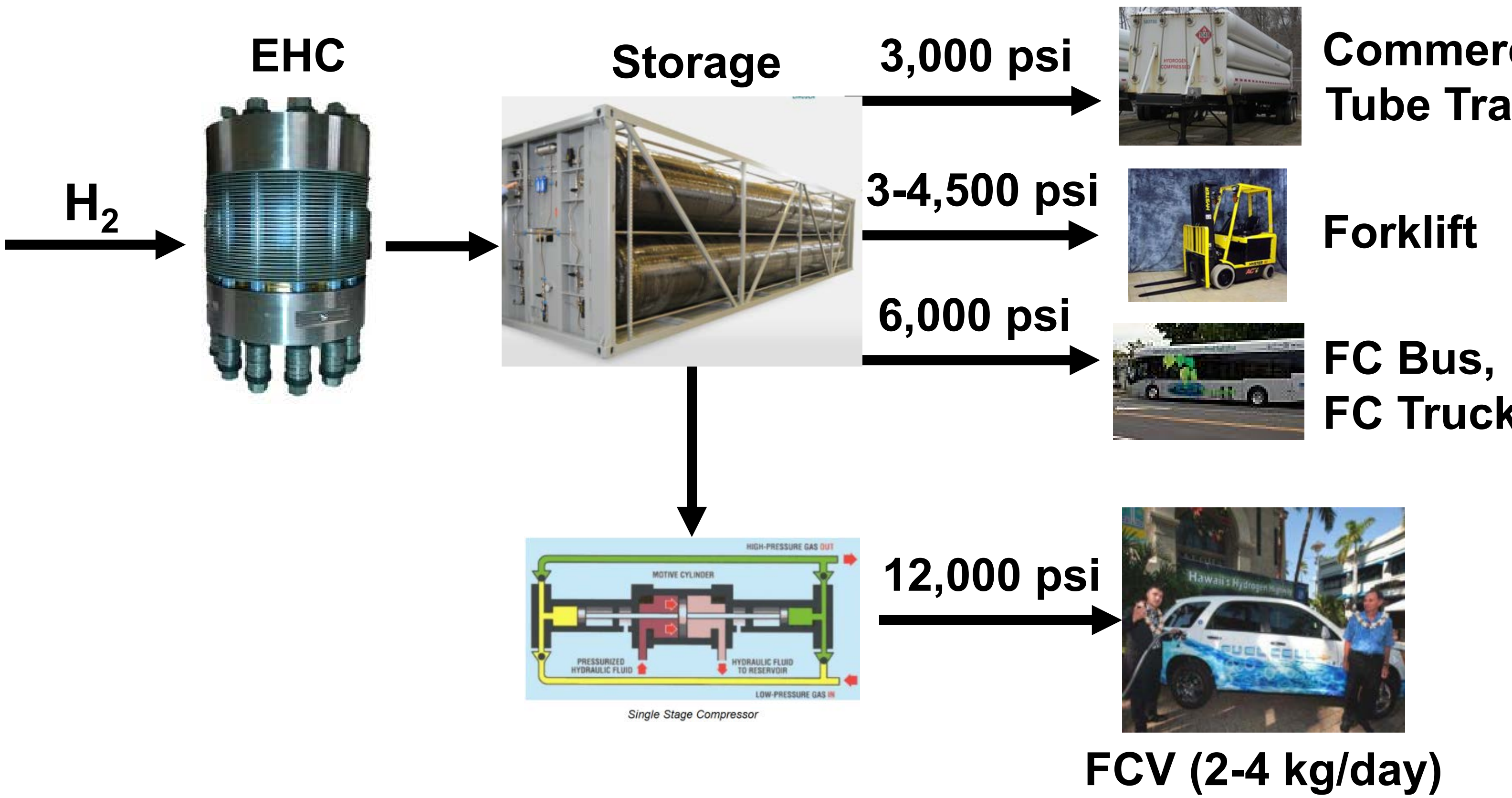
Current Density	100 mA/cm^2	200 mA/cm^2	400 mA/cm^2	1,000 mA/cm^2
150-cell stack 82 cm^2	1 kg/day	2 kg/day	4 kg/day	**10 kg/day**
Thermal Management	Convection Cooling (static)	Convection Cooling (forced)	Improved Convection Cooling (high-conductivity fins)	Enhanced Convection Cooling (liquid)

Phased capacity addition required by the emerging refueling infrastructure is easily met by increasing number of building blocks at a given site

FuelCell Energy

Sustainable Innovations

Hybrid EHC for Multiple Applications



The Hybrid System Minimizes the Risk for Commercialization

Collaborations

Prime

- **FuelCell Energy, Inc. (Industry):**
  - **System development and application engineering**
  - **Membrane and electrode design and fabrication**
  - **Validation testing**

Subcontractor

- **Sustainable Innovations, LLC (Small Business):**
  - **Cell and stack design, modeling and fabrication**
  - **Scale-up design and fabrication**
  - **EHC stack cost reduction and estimates**

Proposed Future Work

- **Complete endurance testing of single cell and 30-cell stack**
- **Develop building block design for 10 kg/day capacity for refueling and other commercial applications (3,000 psi stage 1)**
- **Estimate cost reduction benefits of hybrid EHC system for gaseous and liquid hydrogen refueling**
- **Prepare final report**

Achievements in EHC Technology Development

Parameter	Program Goals	Current Status
Hydrogen Product Pressure	Up to 3,000 psi building block, 6-12 kpsi	**12,800 psi single stage** **6,000 psi 2-stage** ✓
Hydrogen Inlet Pressure	5 - 300 psi	**0 – 2,000 psi** ✓
Compression Ratio	Up to 300:1	**300:1** ✓
Hydrogen Recovery Efficiency	90 - 95%	**>98%** ✓
Hydrogen Flux	500 -1,000 mA/cm^2	**500-1,000 mA/cm^2 for >10,000 hrs (185 cm^2 cell)** ✓
Hydrogen Capacity	2-4 lb/day at 3,000 psi	**2 lb/day at 3,000 psi** **(up to 10 lb/day at SI)** ✓
Endurance Capability	1,000 hrs at 3,000 psi	**>10,000 hrs at 3,000 psi** ✓
Compression Efficiency	<10 kWh/kg at 3,000 psi	**3-12 kWh/kg from <30 to 3,000 psi** ✓

Successfully Met all Program Goals

Project Summary

Relevance: **Provide highly efficient, reliable and cost-effective hydrogen compression (up to 6,000/12,000 psi)**

Approach: **Develop electrochemical compressor – solid state device**

Technical Accomplishments:

- **Scaled-up to 30-cell stack with low-cost high-reliability thermal management**
- **Operated >16,000 hrs in 185 cm^2 cell at high H_2 recovery (≥ 95%)**
- **Demonstrated 2 lb/day capacity at 3,000 psi in 185 cm^2 stack**

Collaborations: **Active partnership with industry (Sustainable Innovations) on materials, design and fabrication**

Proposed Future Work: **Scale-up to taller stack to further increase throughput and lower the cost**

Technology Transfer Activities

- Discussed with LLNL EHC system for compression of LH_2 boil-off for GH_2 vehicle refueling
- Discussed with NREL potential siting of EHC at ESIF
- Identified applications of EHC in Tri-gen systems for FCV refueling in California
- DOE-NASA meeting to explore EHC applications

Acknowledgement

- FCE: Pinakin Patel, Ray Kopp, Jonathan Malwitz, Paul Pinard
- Sustainable Innovations, LLC: Trent Molter and team
- DOE: Erika Sutherland, Dave Peterson