2010 DOE Hydrogen Program Review

Advanced PEM Based Hydrogen Home Refueling Appliance (SBIR Phase I)

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Project ID# PD064

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OverView

Timeline

- Start July 2009
- End January 2010
- 100% Complete

Budget

- Total project funding
  - DOE share = $100,000
  - Contractor share = none
- Funding received in FY09 = 100%

Barriers

- Barriers addressed

  Electrolyzer Based Home Refueling System for Passenger Vehicles:
  - Feasibility Analysis
  - Safety Analysis and Codes
  - Projected Costs of system and product hydrogen

Partners

- Project lead

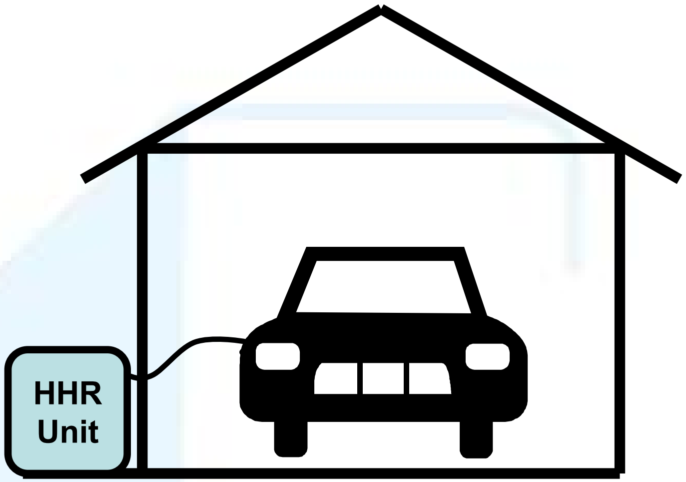
  ElectroChem, Inc.

Objectives - Relevance

- Develop Simplified PEM electrolyzer appliance design that supports high efficiency and safe operation at a scale suitable for home refueling of passenger fuel cell vehicles.
- Determine technical feasibility, physical operating parameters, expected reliability and suitability for home use.
- Determine safety requirements and applicable codes.
- Analyze unit manufactured cost, reliability, operating and maintenance cost and total costs.
- Examine market impact and acceptability.

Hydrogen Refueling @ Home - Relevance

- **Fuels Hydrogen Vehicle Market "One-Car-At-A-Time"**
- **Use "Off Peak" Electricity for low cost H2 fuel @Home**
- **Safe storage of H2 directly in vehicle tank**
- **Convenient to Install and Use**
- **Solves the "Infrastructure Challenge"**
- **Most Rapid Market Expansion**
- **Lowest Investment Risk**



- **No Operating Manpower Cost**
- **No Real Estate Cost**
- **Low Excess Capacity**

Provides simplest, cleanest and most reliable H2 production means.

Plan & Approach

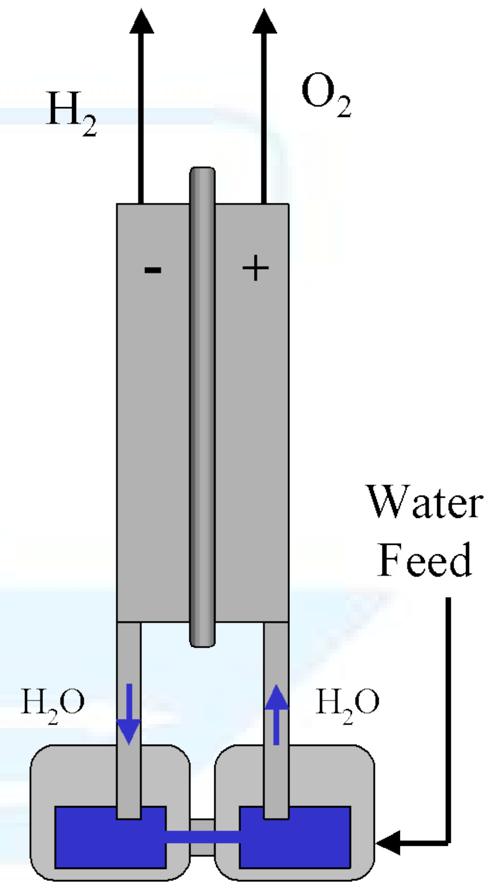
- Feasibility – Define operating requirements based on necessary performance and customer requirements. (capacity, location, noise, safety, maintenance.)
- Prelim Design – Specify acceptable designs and detailed performance specifications. (Power, size, operating schedule, life, efficiency, feed requirements)
- Design Analysis – Perform bottoms-up and top-down cost analyses for the production of up to 500,000 units/yr. Identify applicable safety codes and primary safety factors. Define required maintenance .
- Process Analysis – In a bottoms-up approach, determine complete hydrogen cost analysis using H2A.
- Technology Development Plan – Identify key technical factors requiring further development.

Strategic Approach

- Eliminate factors (storage, manpower, real estate) driving high costs of forecourt H2 fueling systems.
- Design system around typical driver needs.
- Implement the system simplifications allowed by the IFF design.
- Determine all the necessary components in 3 complete versions of a home refueling electrolyzer system that assume differing technical advancements over current technology.
- Determine safety factors by comparison with similar solutions already “codified”.
- Determine bottoms-up cost ,and leverage prior analyses targeting fuel cell volume manufacturing for vehicle production.
- Compare with competitive electrolyzer system costs via power-rule scaling.

ElectroChem's Approach

- The Integrated Flow Field (IFF) allows for a passive liquid water feed and phase separation inside each cell. <u>Eliminates water circulation.</u>
- Radically simplifies system design, lowers cost, reduces moving parts, and improves reliability.
- Small size for home refueling allows simplified direct air cooling of system.
- Can be scaled down efficiently.
- Leverages PEM technology & cost advances made in fuel cells for vehicles.



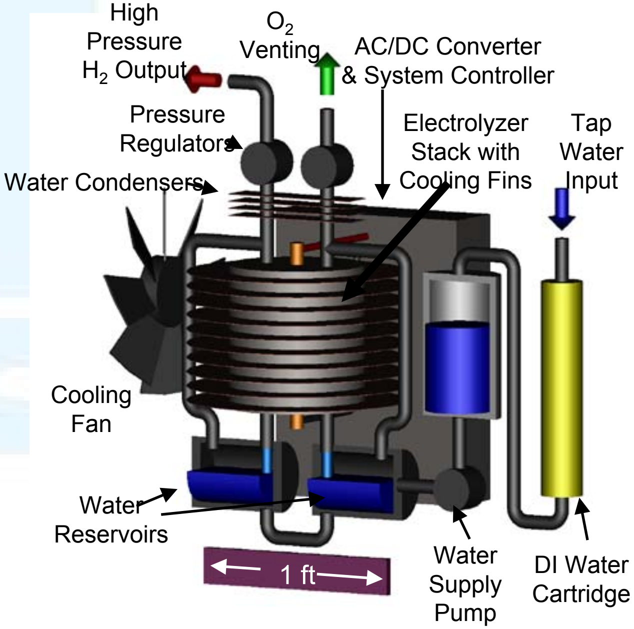
IFF Concept

Accomplishments - Feasibility

- IFF Electrolyzer systems can be economically scaled to home refueling capacity if simplified in operation and number of moving parts.
- IFF electrolyzers can be designed to be inherently safe, environmentally friendly, and suitable for home refueling.
  - Prior ElectroChem market study indicates acceptance of home refueling if size, cost, reliability, and safety goals can be met.

Parameter	Value	Units
Hydrogen Production Capacity	1	kg/day
Output Pressure	5000	psi
Period of Operation	8	hrs
Operating Voltage	240	Volts (AC)
Daily Commute	35	Miles
Mileage Efficiency of Vehicle	67.5	Miles per kg
Annual Mileage	12,000	Miles
Capacity Utilization	50%	
Product Life	10	Years

Design Goals



Accomplishments - Prelim Design

- Three Designs Developed
  1. High pressure IFF electrolyzer
  2. Medium pressure IFF Electrolyzer & Compressor
  3. Medium Pressure Conventional Electrolyzer & Compressor
- Electrical supply (6.5 kW) and tap-water (deionized) are compatible with home use.
- Off Peak (low electricity cost) operation has sufficient capacity for daily commuting.
- Size (2’ x 2’ x 2’) and noise (45 dB or less) compatible with home installation outside garage.
- Inherently safe because of direct H2 storage in vehicle.

Accomplishments - Safety Analysis

- Safety Codes Reviewed
  - US national electric and fire codes
  - SAE vehicle safety standards
  - ASME process piping standards
  - International Fuel Gas Code
- In-Vehicle storage
  - Utilizes vehicle safety system
  - SAE J2579
- Electrical Power System
  - Similar to Electric Vehicle system
  - Covered by Class 2 EVSE (NEC625)
  - Minor Modifications needed for NFPA 52
- Compression & Dispensing
  - Similar to CNG Home Dispensing
  - Careful design of air venting around dispensing hose
  - Minor Modifications needed for NFPA 52
- Internal Gas Hazard
  - Contained volume is minimized
  - Contained flammable gas hazard is small
- Installation
  - Similar to CNG Home Dispensing
  - Minor Modifications needed for NFPA 52

Except for Minor Modifications to Existing Codes

Electrolyzer Based Hydrogen Home Refueler is compatible with safety standards

Accomplishments – Bottoms Up System Cost

- Detailed parts cost estimates across all 3 designs
  - Assume manufacturing volume of 500,000 units/yr.
  - Utilize state-of-the-art materials usage, & 10 yr life.
  - Assume stack efficiency of 70%.
  - Extrapolate component costs from comparable available items
  - Follow approach used in fuel cell vehicle cost estimations.[1]
  - Power Supply costs estimated from Level 2 EV Charging stations estimates.[2]

[1] E.J. Carlson, P. Kopf, J. Sinha, S. Sriramulu, and Y. Yang, Cost Analysis of PEM Fuel Cell Systems for Transportation, *Subcontract Report* NREL/SR-560-39104, December 2005, Subcontract No. KACX-5-44452-01.
[2] Kevin Morrow, Donald Karner, James Francfort, "Plug-in Hybrid Electric Vehicle Charging Infrastructure Review", Final Report, Battelle Energy Alliance, Contract No. 58517, November 2008.

Accomplishments - Bottoms Up System Cost

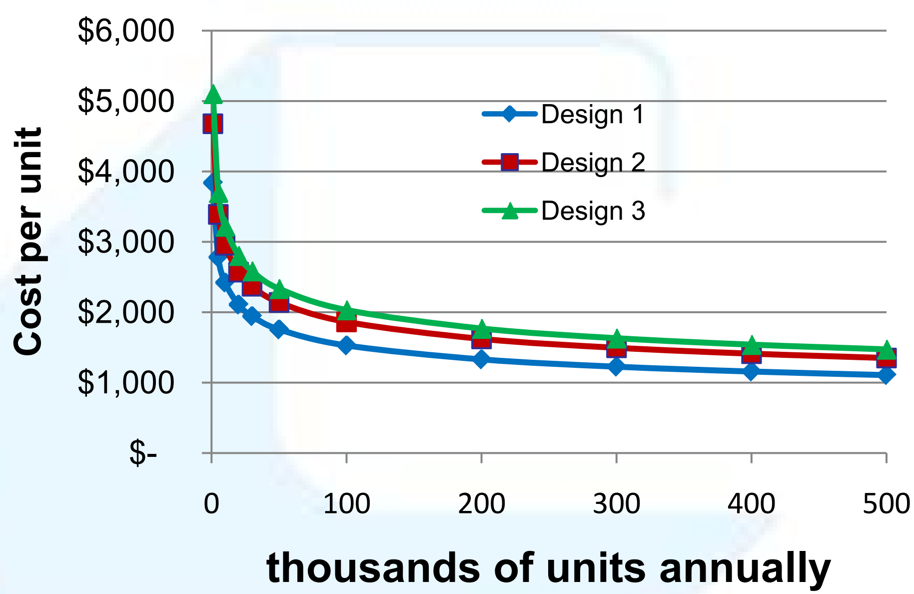
Manufactured Cost

	Design 1	Design 2	Design 3
Compressor System	$0	$265	$265
Electrolyzer System	$637	$ 614	$736
Power Supply & Controls	$471	$ 471	$ 471
Manufactured Cost	$1,108	$1,350	$1,473
Relative Cost	1.00	1.22	1.33

Total Hardware Cost

Installation Costs	$ 796	$ 796	$ 796
Total Installed Cost	$1,903	$2,145	$ 2,268
Yearly maintenance	$50	$50	$ 50

Manufactured Cost – Volume Scaling



Conclusions

IFF Designs (1 & 2) are significantly lower cost

Total Installed Cost is ~$2k

Accomplishments
System Cost – Power Rule Scaling

- Alternative Cost Estimation Method
  - Provides a “Reasonableness” check
- Power Rule Scaling
  - Cost-per-unit declines with increased number made
  - Cost-per-unit increases less rapidly as unit size increases
  - Costs Scale via a simple power law (such as $C = K N^{\alpha}$)*
- Rule applied to Conventional Electrolyzer scaled down to home refueling size, but increased in number to meet vehicle sales

System Design	Manufactured Cost
Power Rule Scaled - Current Technology	$2,313
Power Rule Scaled - Future Technology	$1,275
IFF High Pressure (Design 1)	$1,108
IFF Med Pressure (Design 2)	$1,350
Conventional Med Pressure (Design 3)	$1,473

<u>Conclusion</u>

Nearly Identical Results
To Bottoms-Up Analysis

* Parameters adapted from cost data on related technologies.

Accomplishments - Process Analysis

- Use Bottoms-Up system costs and estimate H2 fuel costs via H2A

Key Assumptions

- Utilization 50% (equivalent to 4 hrs/day)
- Off Peak Electricity ($0.055/kW/hr)
- Financing debt at 5%, 10 yr duration
- Construction period = zero
- Land Costs = zero
- Operator Manpower = zero

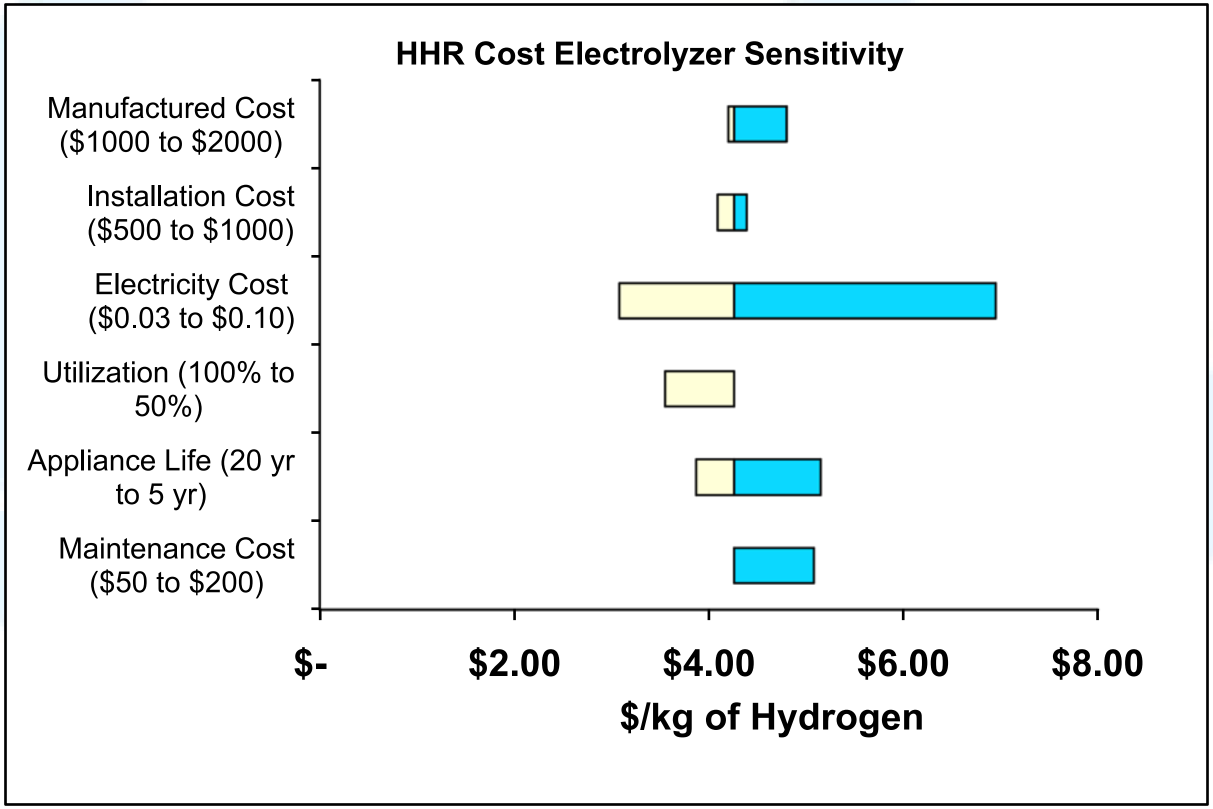
Home Refueling Case	Utilization	H2 Fuel Cost	Electricity cost %	Annual Driving	Annual Fuel Cost
Design 1 – HHR-IFF, No Compressor	50%	$4.26	67%	12,000 miles	$786
	100%	$3.55	80%	24,000 miles	$1311
Design 2 – HHR-IFF, On-board compressor	50%	$4.39	65%	12,000 miles	$810
	100%	$3.62	79%	24,000 miles	$1337
Design 3 – HHR Conventional PEM, On-board compressor	50%	$4.47	64%	12,000 miles	$825
	100%	$3.66	78%	24,000 miles	$1351

Accomplishments - Process Analysis

Cost Sensitivity

– System Design 1

– 50% Utilization



Accomplishments
Fuel Cell Car Market Impact

- **Problem:** H2 forecourt stations will be Highly Underutilized during the first 10 yrs of market growth
- **Solution:** Home refueling reduces wasted infrastructure by “One-Car-At-A-Time” approach.
- **Public Benefit:** Home refueling reduces the refueling infrastructure cost by 50% during the first 10 yrs of market growth. (10 million vehicles by 2025.)

- **Problem:** To control cost H2 forecourt stations will be regionally limited, crippling market growth
- **Solution:** Home refueling eliminates regional limitations by bringing fuel to the user.
- **Public Benefit:** Home Refueling allows market to grow at maximum rate.

Collaborations

- EPRI supported effort demonstrated fundamental feasibility of IFF design

- EPRI consultation on current program (Dan Rastler)

Proposed Future Work

- Demonstrate complete system operation of IFF based PEM electrolyzer
- Develop membranes for high pressure PEM electrolysis
- Develop small sized H2 compressors
- Encourage modifications for safety codes for hydrogen home refueling systems.

Summary

- Home refueling advances hydrogen vehicle market by solving “Infrastructure Challenge”
- Technologically Integrated Flow Field (IFF) provides the lowest possible system cost, simplest design, and highest reliability
- Mass production of low cost system and operation with off-peak electricity provides cost-competitive H2 fuel.
- Electrolyzer appliances are compatible with safe installation and operation at the home.
- Modest sized units can provide refueling for passenger vehicles at 5000 psi and higher.

For More Information

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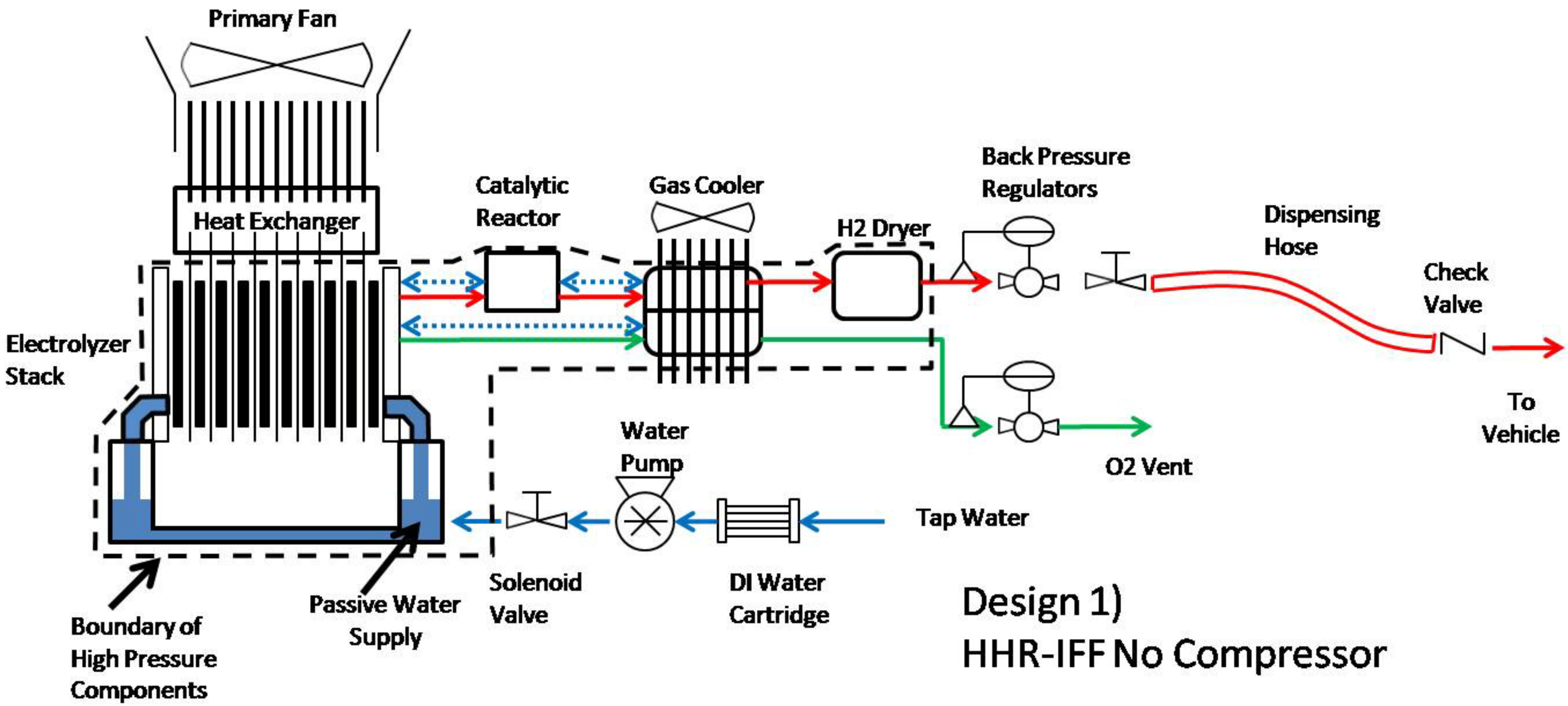
Supplemental Slides.

Accomplishments - Feasibility

Factor	Reformer	Alkaline Electrolyzer	IFF PEM Electrolyzer
Toxic Chemical Hazard	Potential for poisonous CO or natural gas leakage	Uses Concentrated Caustic Soda	None
Hydrogen Purity	Requires Purification	Requires Purification	No Purification Needed
Green House Emissions	CO_2 emitted as byproduct	None	None
Resource Availability	Natural Gas is Not Available Everywhere	Water and Electricity is Every Home	Water and Electricity is Every Home

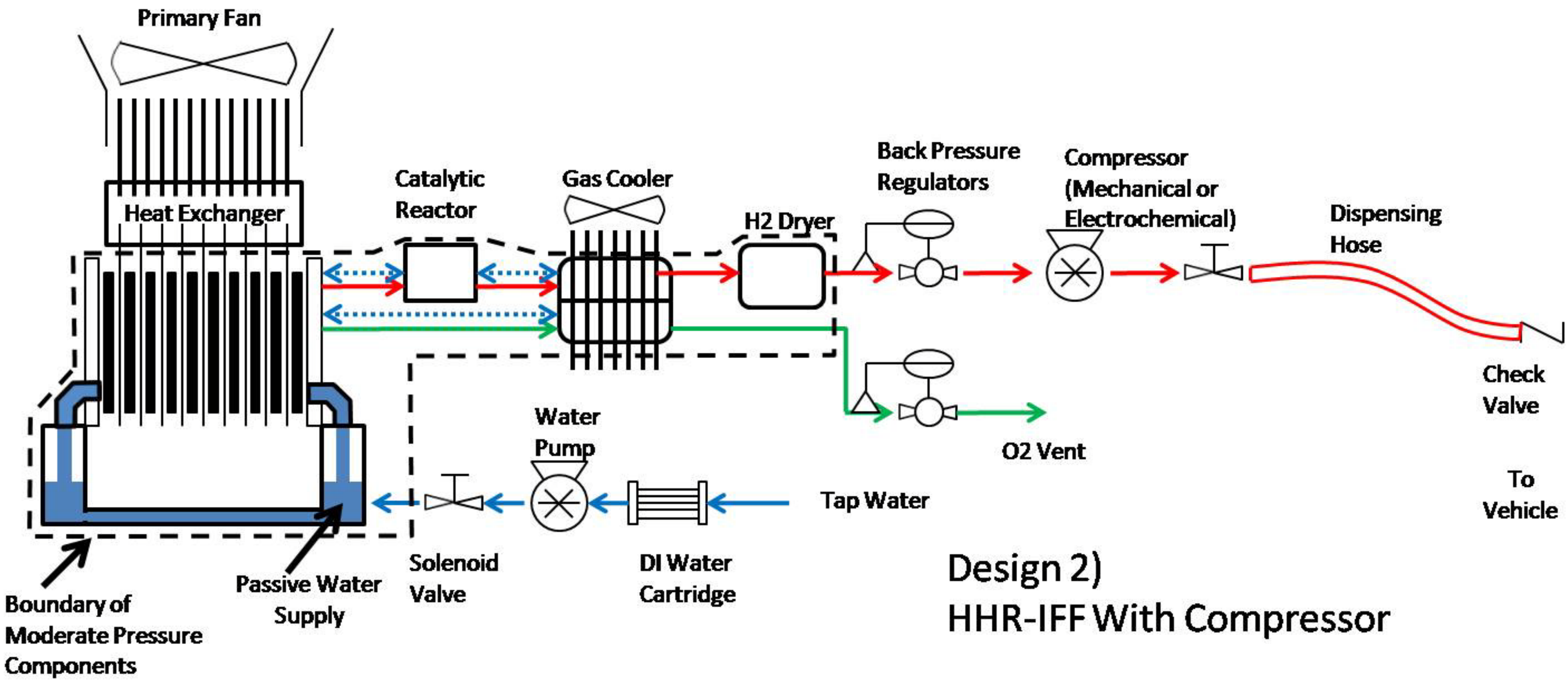
Comparison of fundamental characteristics of competing technologies considered for the HHR appliance. The importance of these factors is that IFF simplifies the design of a PEM-based HHR. Special considerations for feed materials, safety of handling, purity of product hydrogen, or infrastructure needs are not needed.

Accomplishments - Prelim Design



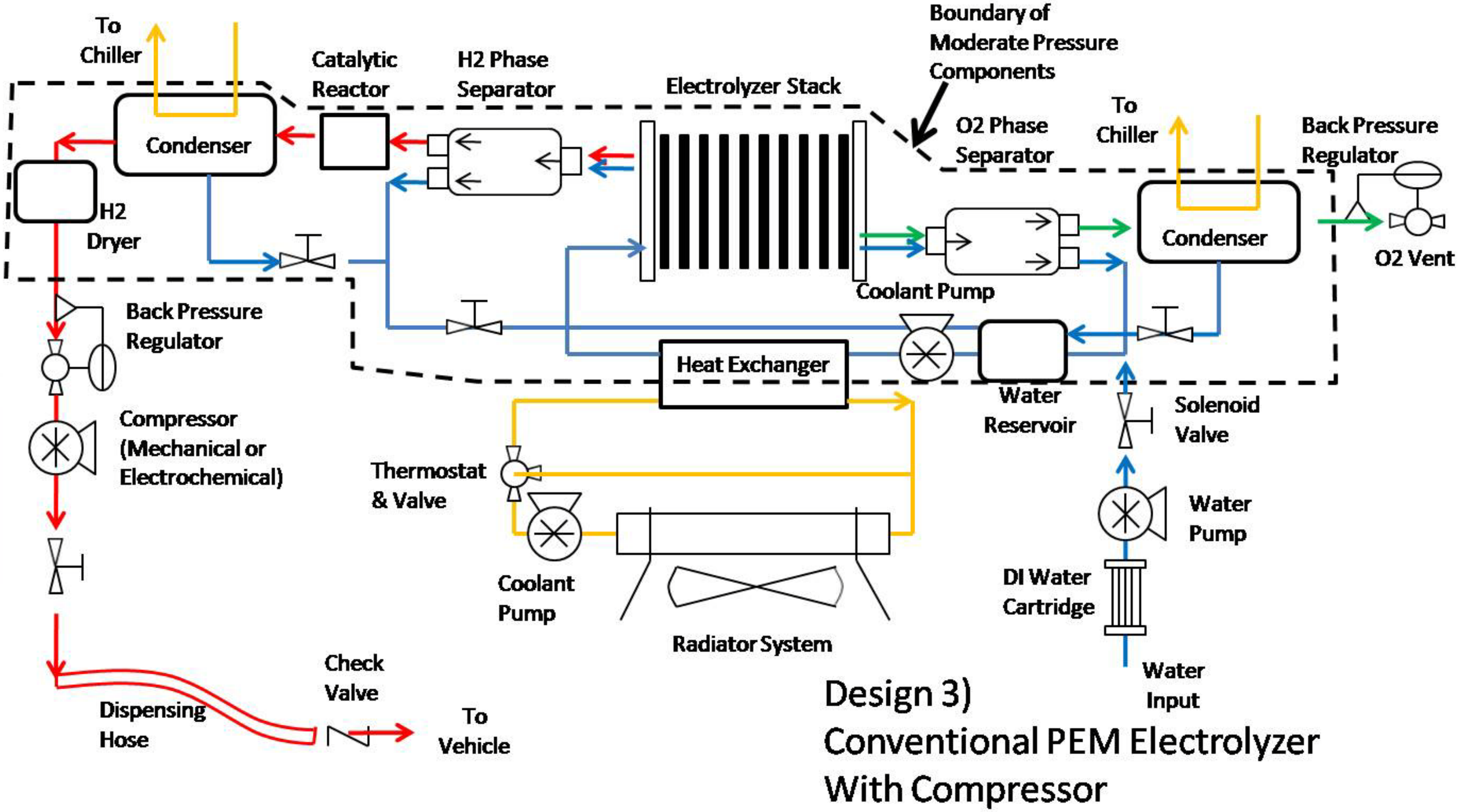
- Schematic diagram showing the important mechanical system components, excluding sensors and electrical controls for the high pressure HHR-IFF electrolyzer system. Note that as much detail as possible is given to ancillary components, since they all contribute to cost.

Accomplishments Prelim Design



- Schematic diagram showing the important mechanical system components, excluding sensors and electrical controls for the moderate pressure HHR-IFF electrolyzer system with a compressor added to reach 5000 psi. Note that as much detail as possible is given to ancillary components, since they all contribute to cost.

Accomplishments - Prelim Design



- Schematic diagram showing the important mechanical system components, excluding sensors and electrical controls for the moderate pressure HHR conventional electrolyzer system with a compressor added to reach 5000 psi. Note that as much detail as possible is given to ancillary components, since they all contribute to cost.

Accomplishments - Bottoms Up System Cost

	Hi - Pres ElectroChem IFF-HHR (Design-1)	Med - Pres ElectroChem IFF-HHR (Design-2)	Med - Pres HHR Conv. Electrolyzer (Design-3)
Catalyst	$127.00	$127.00	$127.00
Membrane	$41.90	$41.90	$41.90
Bipolar & Cooling plates	$15.04	$15.04	$15.04
IFF Flow Field	$7.52	$7.52	
Stack pressure container	$35.53	$9.21	$9.21
Water Resevoir	$11.10	$2.88	$8.63
Heat Exchanger	$18.18	$18.18	$18.18
Catalytic reactor	$2.00	$2.00	$2.00
Gas Cooler, H2 Dryer	$10.00	$10.00	$10.00
Water Supply Pump	$15.00	$15.00	$15.00
DI Water Cartridge	$66.41	$66.41	$66.41
Back Pressure Regulators	$25.22	$25.22	$25.22
Dispensing Hose	$50.00	$50.00	$50.00
Solenoid valves	$10.00	$10.00	$25.00
Cooling Fan	$5.00	$5.00	$5.00
Power Supply & Controls	$471.11	$471.11	$471.11
High Pressure H2 compressor	$0.00	$256.47	$256.47
Buffer tank for mech compressor	$0.00	$8.63	$8.63
Water Circulating Pump	$0.00	$0.00	$24.49
Radiator System, Pumps (2), Thermostat, Valve	$0.00	$0.00	$73.48
H2 Phase Separator	$0.00	$0.00	$2.88
O2 Phase Separator	$0.00	$0.00	$2.88
Hydrogen sensors	$100.00	$100.00	$100.00
System Housing	$44.00	$44.00	$44.00
system assembly cost (5%)	$52.75	$64.28	$70.13
Total System Cost	$1,107.76	$1,349.85	$1,472.66

Accumulated HHR system manufacturing cost for the three designs described above. Note that the manufactured cost for the IFF based electrolyzer systems are substantially lower because several components are not necessary to its operation. This makes the conventional electrolyzer system 33% more expensive that the high pressure IFF version. The primary cost difference points are based on the mechanical compressor and the forced water cooling system.

Accomplishments -
Fuel Cell Car Market Impact

	Forecourt Hydrogen Stations Scenario (Natural Gas Reformer)*	HHR-IFF design PEM Electrolysis
Number of vehicles deployed by 2025	10 million	10 million
Number of Miles Driven	350 billion	350 billion
Hydrogen Fuel Produced	5.4 billion kg	5.4 billion kg
Total Hydrogen Cost (price + Subsidy)	$38B to $43B	$22B to $23B
Estimated Real Fuel Cost	$7 to $8 /kg	$4 to $4.25 /kg
Federal Subsidy	$27B	$7B

Comparison of investment costs of forecourt infrastructure costs against home refueling. The "at risk" investment during this transition period is nearly cut in half by the deployment of the HHR system. This reduction in risk allows for a reduction in federal subsidy by a factor of four.

**Analysis of the Transition to Hydrogen Fuel Cell Vehicles and the Potential Hydrogen Energy Infrastructure Requirements,* OAK RIDGE NATIONAL LABORATORY, March 2008.

Proposed Future Work

Technology Development Plan	1sr Year				2nd Year			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1. Build a High pressure electrolyzer								
Usg existg Integrated Flow Field (IFF) and low gas crossover membrane technology								
2. Test the High pressure IFF electrolyzer								
Internal water management Coolg/Dryg Temperature control/Pressure regulation Safety control element								
3. Reduce Crossover								
Improve low gas crossover membrane								
4. Develop Small H_2 Compressor								
Test with vehicle tank Safe refuelg process								
5. Design a Balance of Plant								
Simpler component design Computer microprocessor								
6. Test the Balance of Plant								
Safety evaluation Installation cost study								