DFMA Cost Estimates of Fuel-Cell/Reformer Systems at Low/Medium/High Production Rates

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Project Relevance/Objective

Freedom Car Technical Barriers Addressed:

Fuel Flexible Processors Technical Barriers

N: Cost

Component Technical Barriers

O: Stack Materials and Manufacturing Cost

Objective:

Prepare technology-based cost estimates of complete fuel cell-reformer systems at low/medium/high manufacturing rates to assess the current status and identify the most pressing cost barriers.

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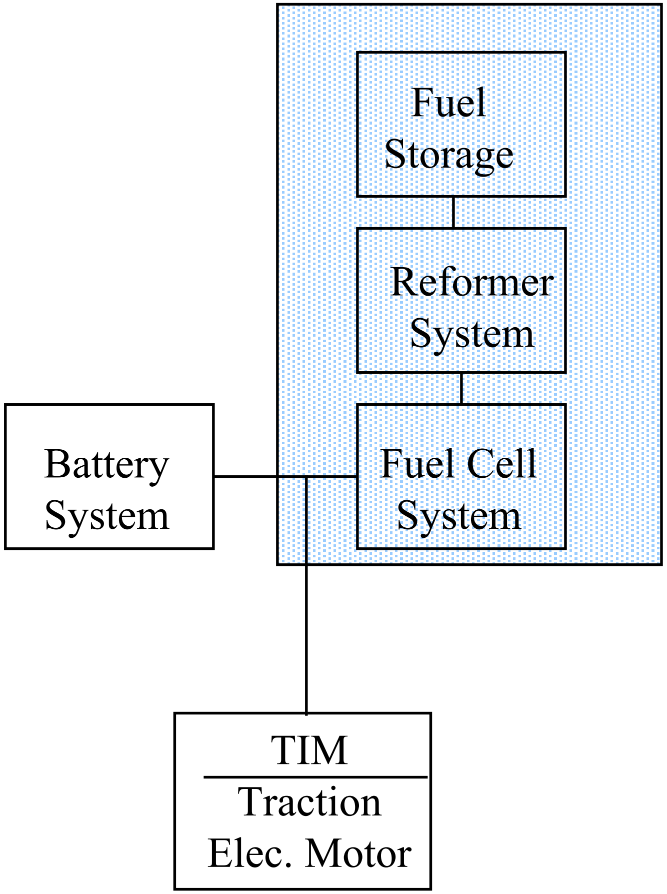
Project Approach

1. **Prepare designs of complete automotive FC power systems:**
   - Onboard gasoline fuel processor and PEM fuel cell system
   - Direct hydrogen fuel cell system (with 5kpsi H_2 storage)
2. **Determine costs for system production rates using DFMA* methodology:**
   - DFMA= Design for Manufacturing & Assembly
   - 500/10,000/30,000/500,000 vehicles per year
3. **Consider Current Year Technology** (i.e. no dramatic forward projections)
4. **Perform Annual Cost Updates**
5. **Conduct Investigations on Selected Topics**

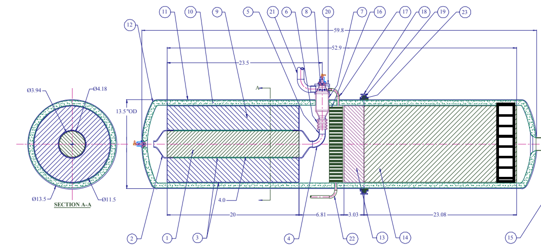
* DFMA is a registered trademark of Boothroyd Dewhurst Inc.

Scope of Project



What is included in Project:

- Reformer
  - Fuel vaporizer
  - Burner
  - Reformer
  - Shift beds
  - Gas cleanup

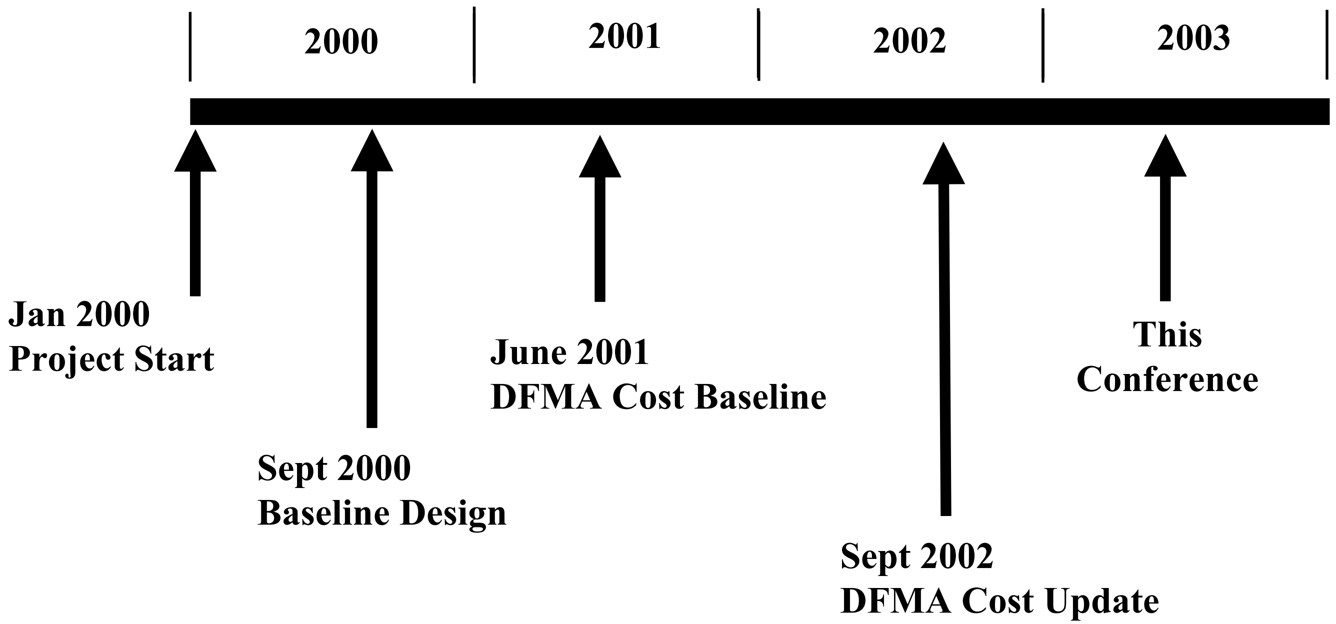


- Fuel Cell System
  - Fuel cell stacks
  - Air supply and humidification
  - Thermal management
  - Water management
- Fuel Supply System
- Power conditioning and electronics (for FC/Ref. Only)
- Electrical System
- Control System
- Sensors
- Safety Systems

What is <u>not</u> included in Project:

- Traction Inverter Module (TIM)
- Traction Electric Motor
- Peak-Power/Start-Up Battery

Project Timeline



Presentations/Reports

July 2001 OATT Report
Sept 2001 Program Review Presen.
June 2002 OATT Report

August 2002 SAE Future Car Congress Presentation
Sept 2002 FreedomCar FC Tech Team Presentation
March 2003 SAE Congress Presentation

Accomplishments/Progress

- 2002 DFMA System costing update
- Sensitivity Analysis of Power Density and Material Costs
- Microchannel reformers & HX to reduce cost- In Progress
- Generation of "Roadmap to Lower System Cost"- In Progress

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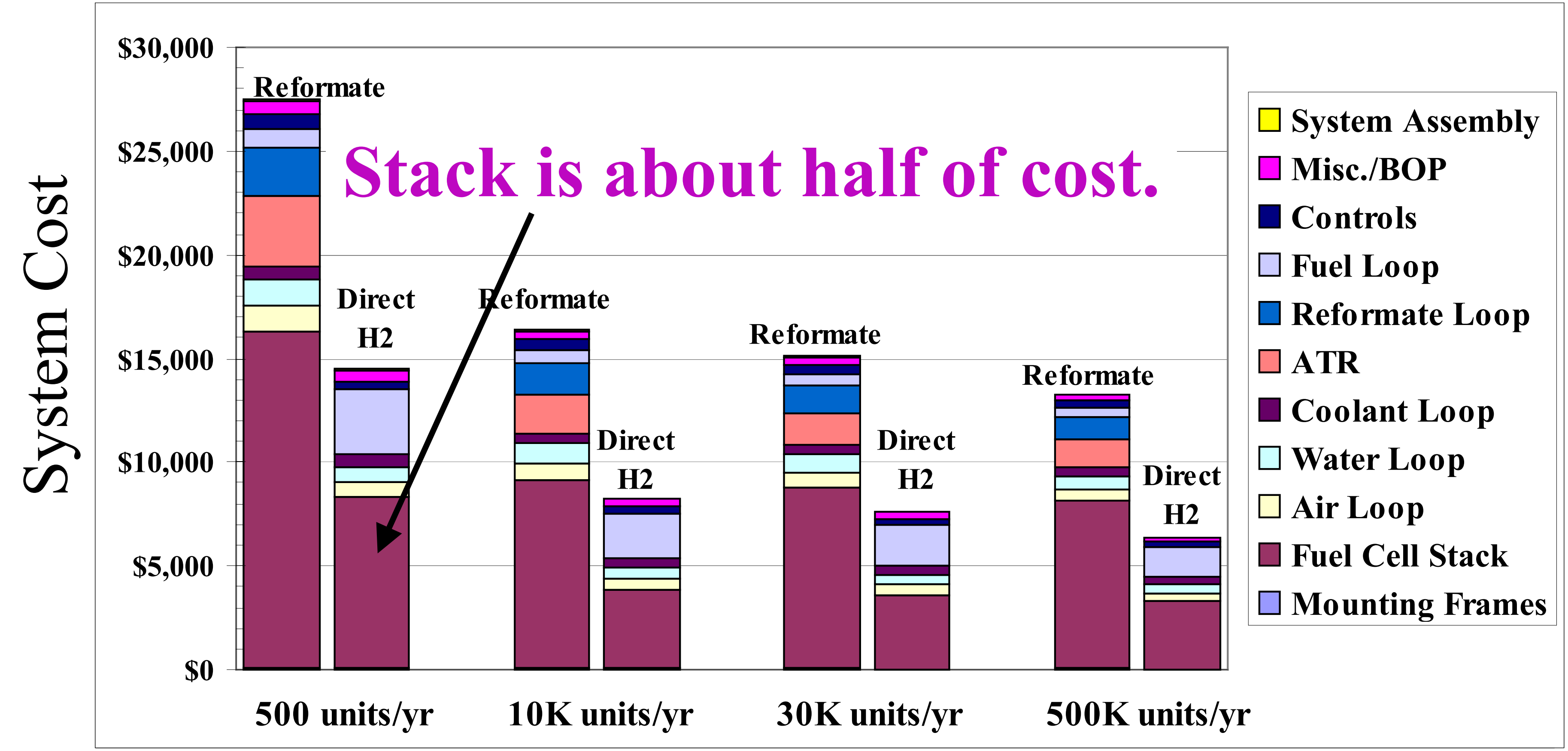
System Comparison

Reformate System vs. Direct H_2 System

(both at 0.7volts/cell)



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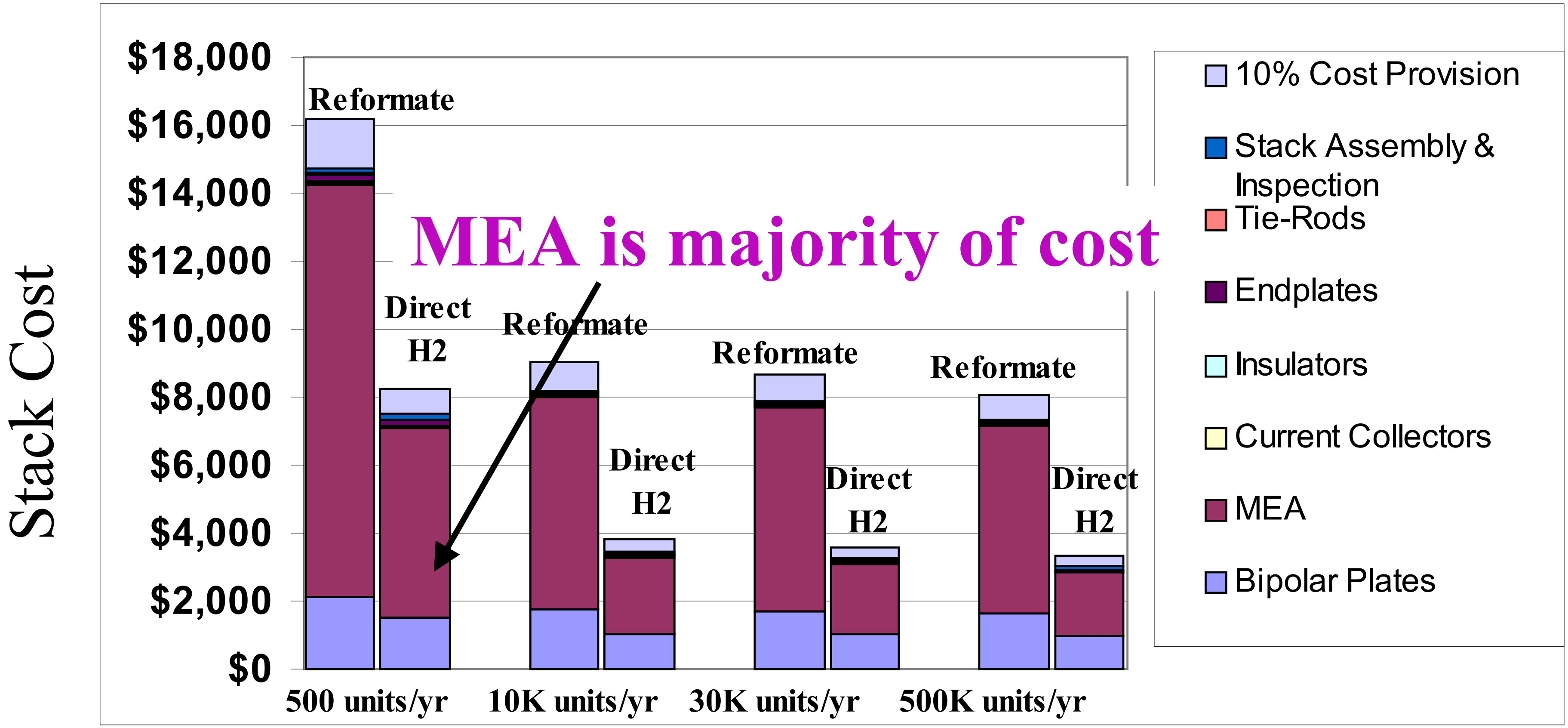
Stack Comparison

Reformate System vs. Direct H_2 System

(both at 0.7volts/cell)



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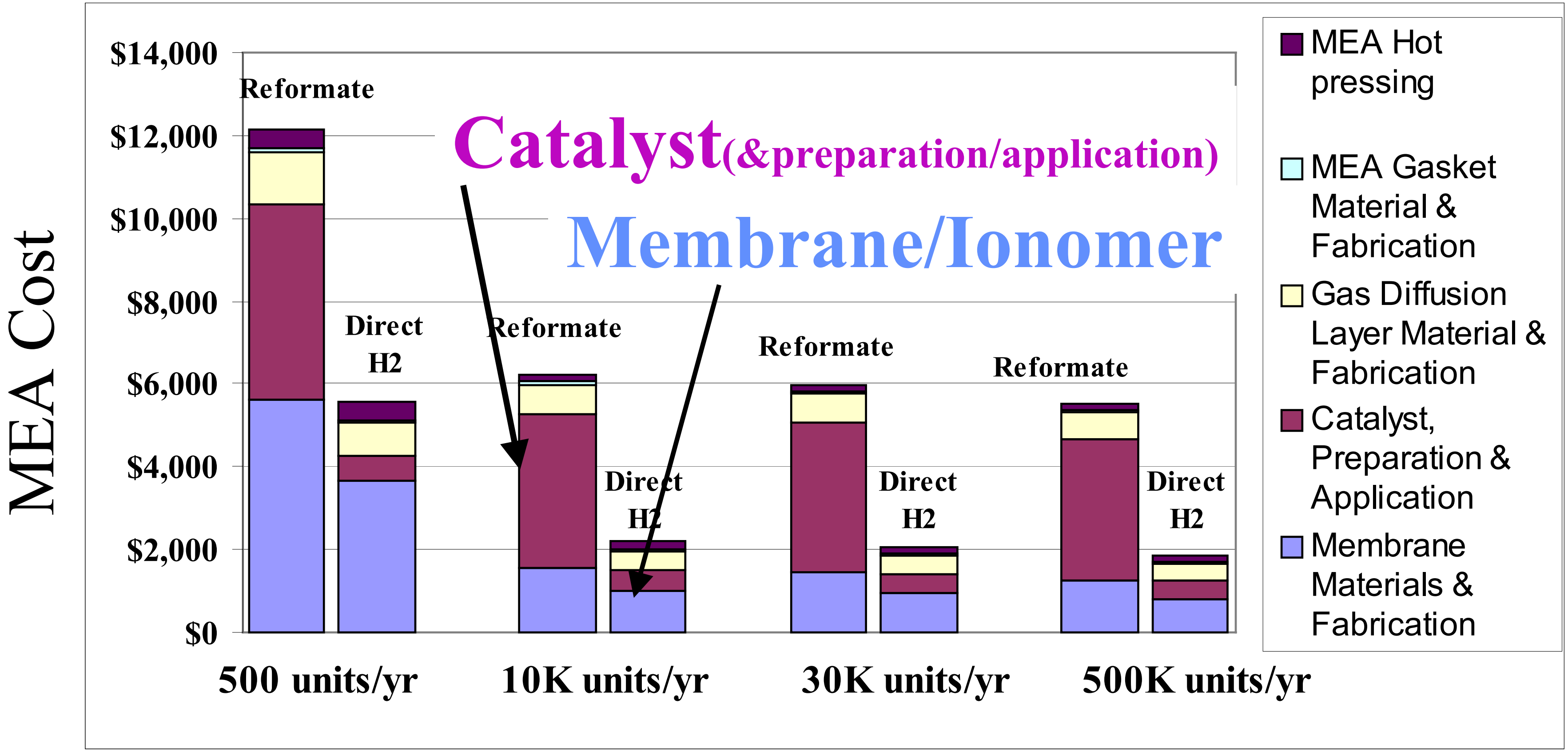
MEA Comparison

Reformate System vs. Direct H2 System

(both at 0.7volts/cell)



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Technical Target Comparison

		FC-Reformer on Tier 2 Gasoline				Direct Hydrogen			
			DOE Technical Targets				DOE Technical Targets		
		DTI 2002 Estimates	2003 Status	2005	2010	DTI 2002 Estimates	2003 Status	2005	2010
Fuel Cell Stack includes stack peripherals	$/kW_{net}$	$193	$200	$100	$35	$88	-	-	-
Reformer System includes reformer peripherals	$/kW_{net}$	$65	$65	$25	$10	-	-	-	-
Total System includes final assembly, BOP	$/kW_{net}$	$266	$300	$125	$45	$157	$200	$125	$45
							includes hydrogen storage		

• **50kW$_{net}$ Systems at 500,000 units per year production volume.**

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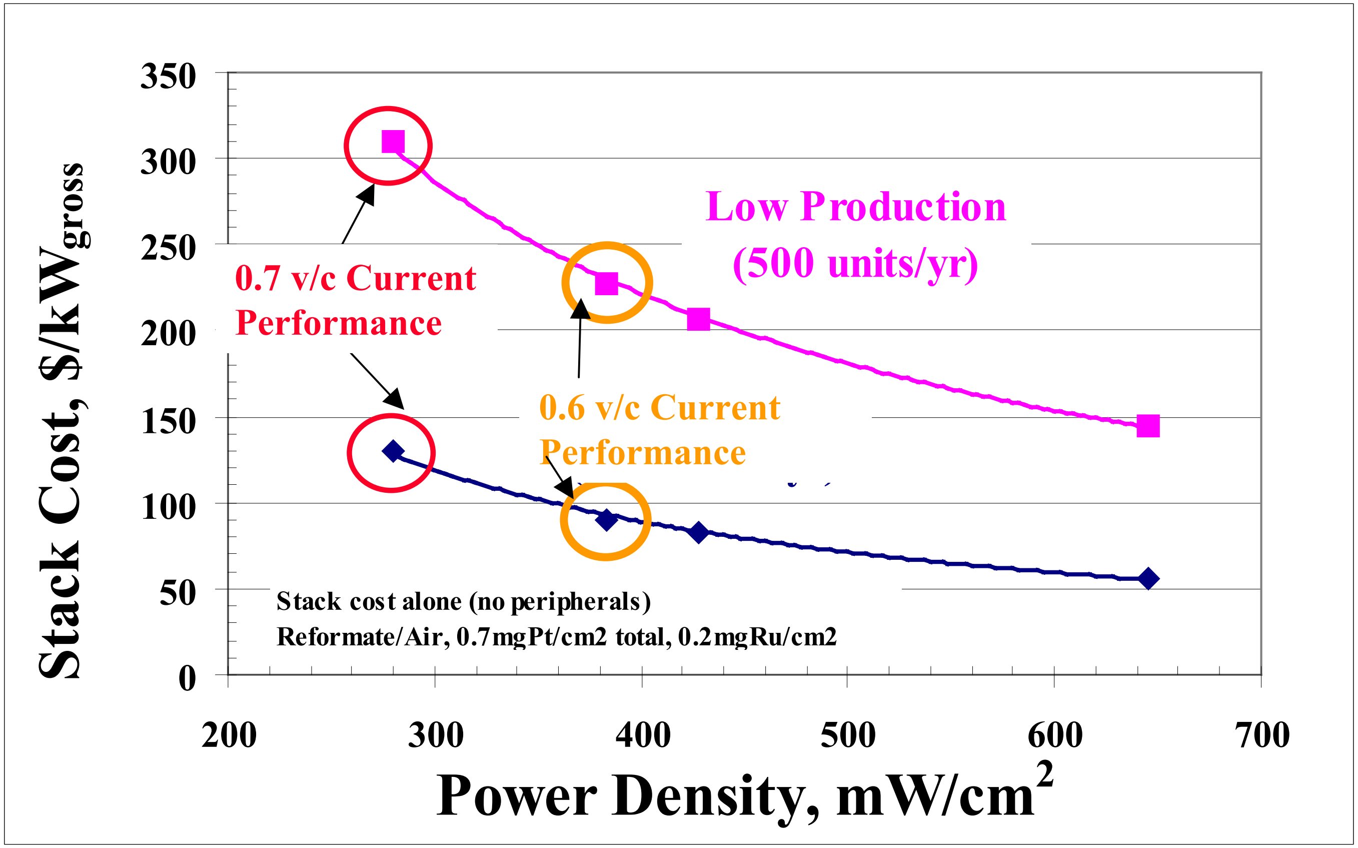
Sensitivity Analysis- Stack Power Density



- Stack resized to maintain constant power
- Stack scaling only slightly off linear
- Power density increase best way to decrease stack cost

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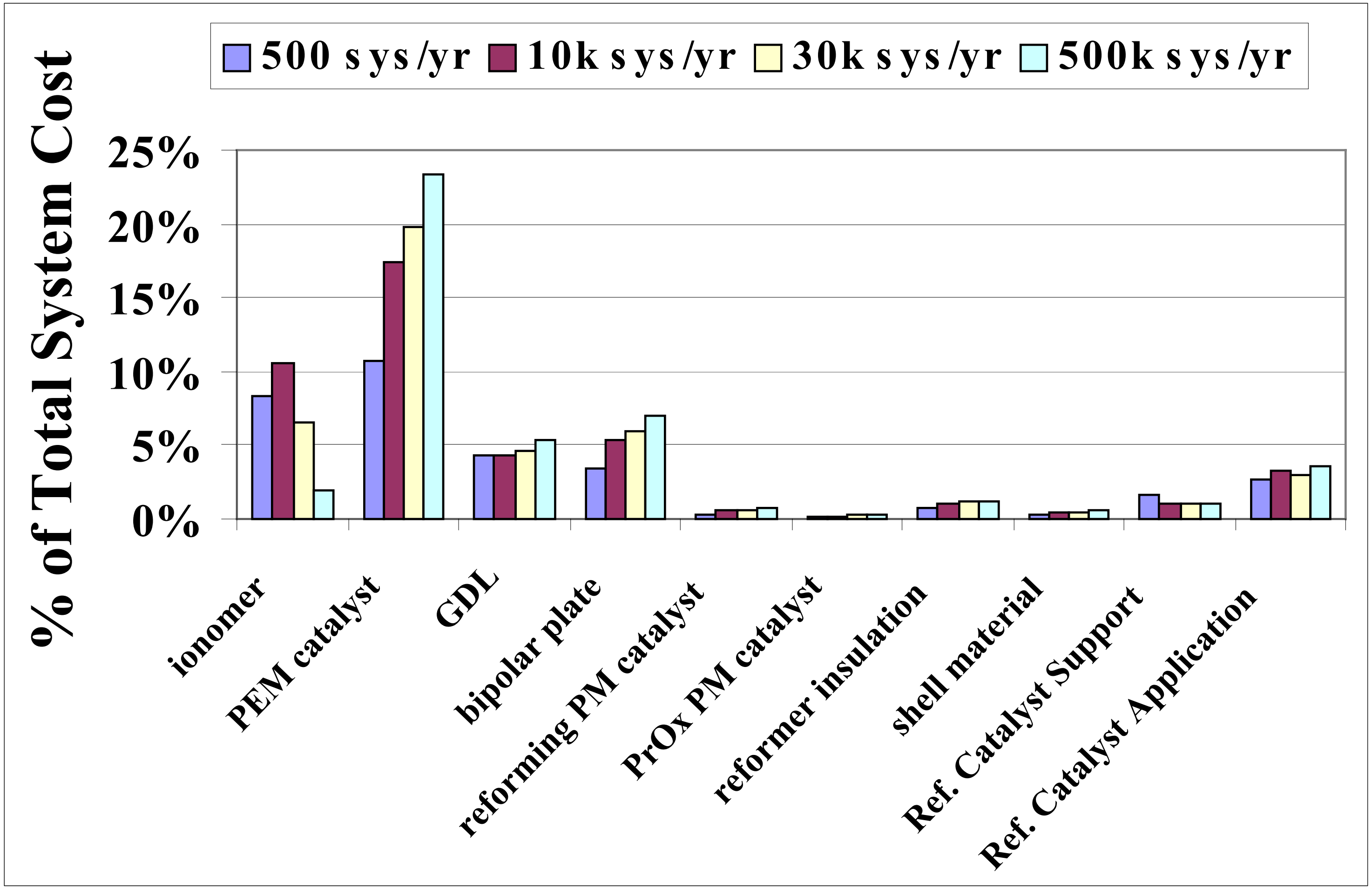
Sensitivity Analysis- Material Cost



- PEM catalyst cost becomes large cost fraction
- Ionomer cost becomes a lesser cost fraction
- Reformate catalyst cost appears not to be significant

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Microchannel Heat Exchangers and Reactors

- **Technology Description**
  - Flow channels with a characteristic dimension of <1 mm
  - High specific heat transfer area
  - Scalable manufacturing processes

- **Why are we considering microchannel components for the fuel processor?** ***Potential for significant improvements over conventional technology***
  - Mass--*Weight reduction could benefit entire system*
  - Volume--*Microchannel architecture allows dense construction*
  - Cost--*Mass manufacturability is possible*

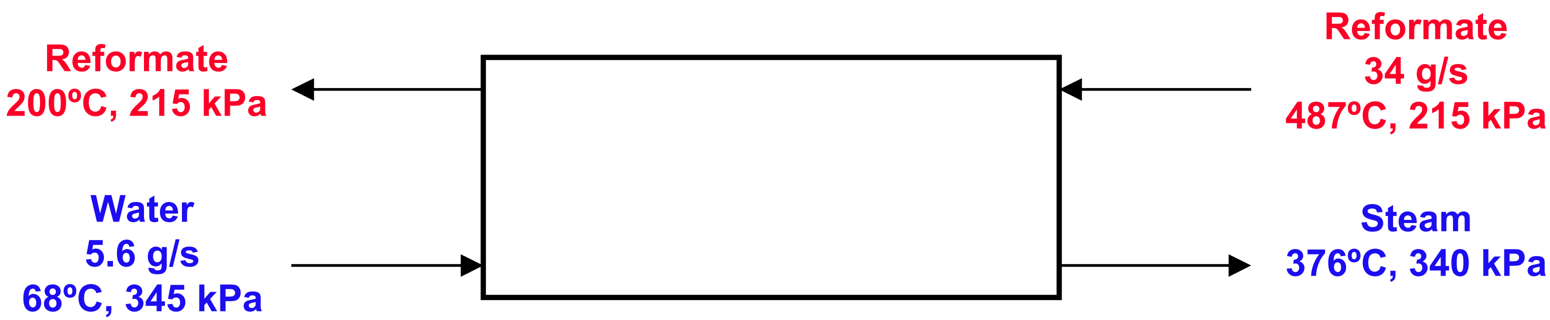
- **Options for microchannel design in fuel processor**
  - Heat exchanger only: *Water vaporizer/boiler*
  - Reactor only: *ATR/SR, WGS*
  - HEX/Reactor: *PROX*

Microchannel Patent Resources

Organization	Patent(s)	Technology
PNNL	6,200,536 6,503,298 5,811,062 6,352,577	Active microchannel heat exchanger; Hydrogen separation/purification utilizing rapidly cycled thermal swing sorption; Microcomponent chemical process sheet architecture; Microchannel laminated mass exchanger
PNNL pending	Applications 20020194990 20020114762 20030072699	Method and apparatus for thermal swing adsorption and thermally-enhanced pressure swing adsorption (Wegeng); Catalysts, reactors and methods of producing hydrogen via the water-gas shift reaction (Tonkovich); Integrated reactors, methods of conducting simultaneous exothermic and endothermic reactions (Tonkovich)
Precision Combustion	6,394,791	Method and apparatus for a fuel-rich catalytic reactor

*InnovaTek is developing microchannel reformers but has not patented the microchannel aspects.

Microchannel Water Vaporizer: *Heat Exchange*



- Current design is a finned tube
- Microchannel vaporizer design criteria
  - Reformate ΔP <1 kPa
  - Considered to be a stand-alone component (i.e., it was not designed to fit into the Baseline fuel processor)
  - Size based on film coefficient calculations for reformate and water, with 5% design allowance

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Water Vaporizer Summary

Heat Duty 16.6 kW

	Heat Transfer Area (cm^2)	Volume (cm^3)	Heat Transfer Coefficient (W/m^2-°C)	Mass (grams)	Cost
Existing Finned-Tube Design	15,600	707	91	2,588	$613 (500/yr); $151 (500k/yr)
Microchannel Design (core only)	6,775	171	359	537	in progress
Microchannel Design (system)	--	669	--	905	in progress

- Microchannel heat exchanger provides mass advantage over finned-tube exchanger
- When system integration components are added, volume advantage of microchannels is slight

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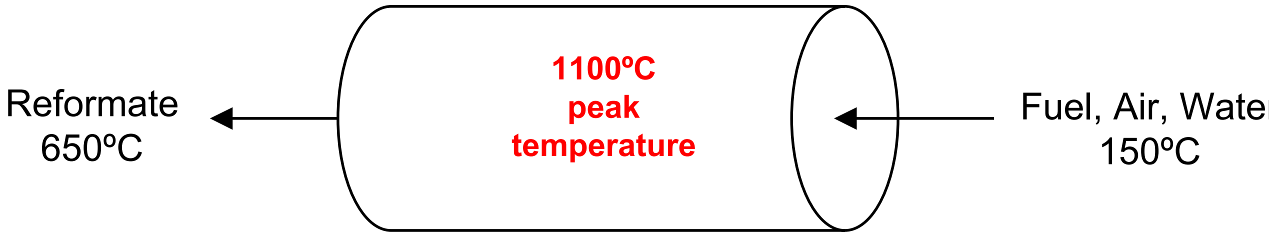
Autothermal Reformer:
Reaction



- Current design is a washcoated monolith
  - Monolith has some attributes of microchannel (~1 mm channels) but lacks the heat exchange capability
  - Washcoat does not appear to be diffusion limited $\Rightarrow$ pores account for only ~10% of resistance to diffusion
- ATR temperatures are prohibitively high for microchannel construction
  - Corrosion allowance (5,000 hours, 980ºC) for the most oxidation resistant alloys is ~75 μm per side, or 150 μm total (Inconel 601 is 375 μm per side)
  - PNNL patent examples at <750ºC use 125 μm plates
- *Adiabatic reactions are not a good application for microchannel components*

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Microchannel Summary & Future Tasks

- Largest gains will be for integrated systems- not discreet component substitutions (baseline design already integrated)
- The water vaporizer could realize mass reduction if it were changed to microchannel configuration
  - 0.9 kg for microchannel vs. 2.6 kg for finned tube
  - *Action item: Calculate cost for mass manufacturing of vaporizer*
- Adiabatic operations (ATR and WGS) would have little or no advantage as microchannels
  - *Action item: Examine WGS with integrated heat transfer—may eliminate one of the WGS stages*
- *Action Item: Consider PROX with integrated reaction/heat exchange*
  - Mass in current design ~7 kg
  - Cost in current design \$505 @ 500/year, \$175 @ 500,000/year

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Plans & Future Milestones

Remainder of 2003

- **2003 DFMA System costing update**
  - Updates to cell performance, catalyst loading, ionomer cost
- **Complete Analysis of Microchannel reactors to reduce cost**
  - component replacement
  - complete microchannel system
  - investigate onboard steam reforming
- **Complete "Roadmap to Lower Cost"**
  - focus on reformer redesign/simplification
  - stack power density
- **Gas Separation for Enhanced Stack Performance**
  - compact Pressure Swing Adsorption (PSA)
  - compact Thermal Swing Adsorption (TSA)

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Plans & Future Milestones

2004

- **Ambient vs. Pressurized Operation Analysis**
- **High Temperature Operation Analysis**
- **Hydrogen Membrane Purification Analysis**
- **Alternate PEM Fuel Cell Approaches**
    - Alternate stack construtuion
    - Fuel Cell Pulsing
    - Alternate Air Compression Approaches

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Collaboration/Interactions

- **Argonne National Lab - reactor design parameters/space velocities**
- **Oak Ridge National Lab - reactor design**
- **PNNL - microchannel performance & design**

- **W.L. Gore & Associates - catalyst loading/FC performance**
- **DuPont - catalyst loading/FC performance**