MICROCHANNEL FUEL PROCESSING

Development of an Efficient, Compact Fuel Processor

Annual National Laboratory R&D Meeting
DOE Fuel Cells for Transportation Program

June 7-8, 2000

Battelle

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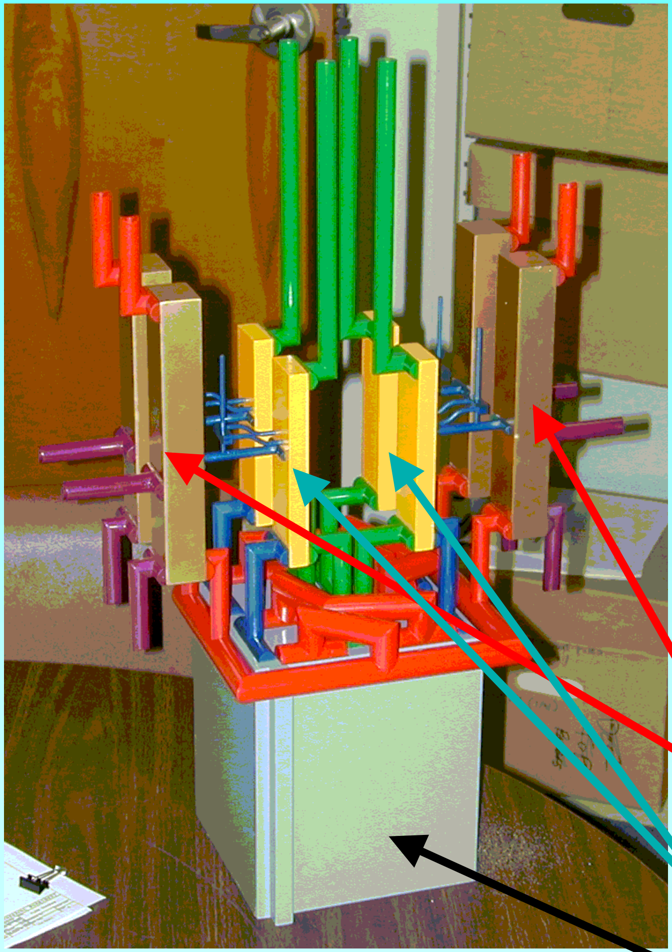
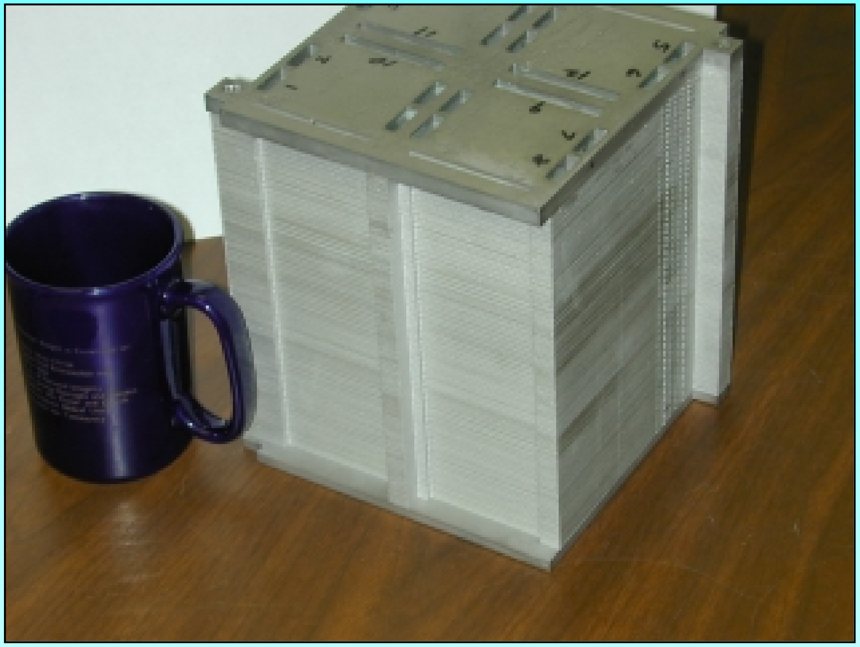
Energy-Efficient Microchannel Fuel Processor Expected To Provide 10 kWe



Bonded 10 kWe Microchannel Reformer

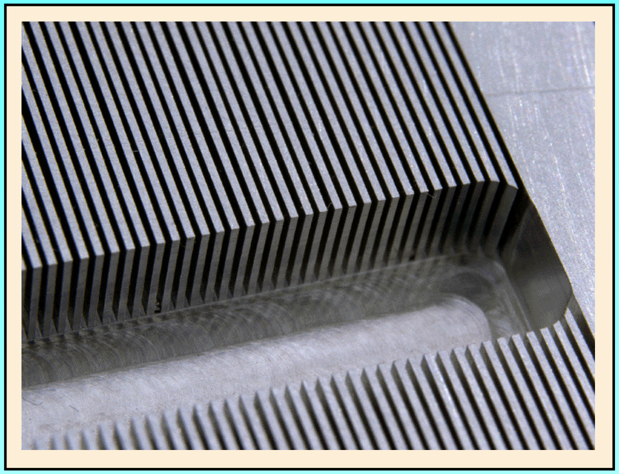


Exhaust Recuperators/Water Vaporizers

Reformate Recuperators/Fuel Vaporizers

Steam Reformer

TECHNICAL APPROACH



- Develop ultra compact reactors, separators and heat exchangers -- for the onboard, automotive production of hydrogen from liquid hydrocarbons -- *based on heat and mass transport advantages that can be realized using engineered microstructures*
- Ultimate Goals for Microchannel Fuel Processor System:
  - Output: Sufficient fuel for 50 kWe PEM fuel cell
  - Volume: < 1.0 cubic foot
  - Cost: < $500/unit (based on 500,000 units per year)
  - Performance: 40-50% system efficiency (including PEM fuel cell)

CONTENT

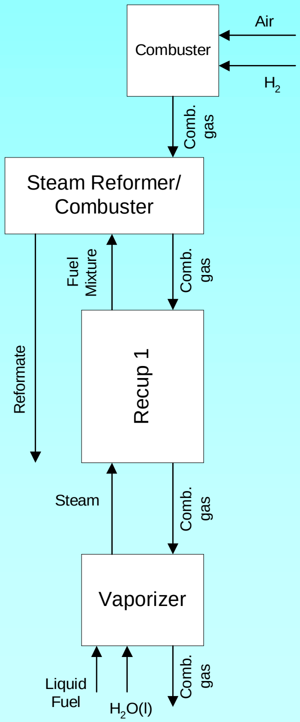
Larry Pederson – Introduction, Approach
Ward TeGrotenhuis – System Efficiency Model, Steam Reforming Reactor Performance
Greg Whyatt – Microreformer Fabrication and Component Performance Results
Bob Wegeng – Summary, Development Plans

Development Timeline Summary

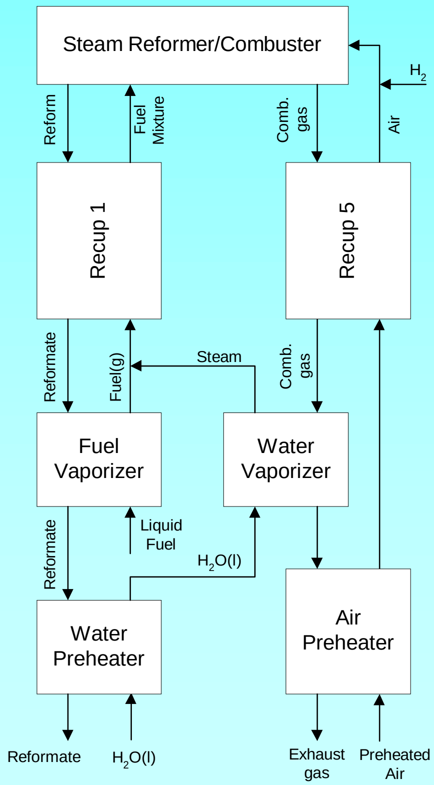
- Previous Efforts at PNNL
  - Microchannel Fuel Vaporizer Demonstrated at 50 kWe (300 mL/min) for Gasoline, With an 0.3 L Volume (1999 R&D 100 Award)
  - Microchannel Steam Reformer Demonstrated at 1 kWe with Isooctane
- Current Effort
  - Efficient 10 kWe Microchannel Steam Reformer/High Temperature Water Gas Shift Subsystem
  - Multi-Stream Recuperative Heat Exchangers and Steam/Fuel Vaporizers
  - Microchannel Condensor with Vapor/Liquid Separation

Integrated Steam Reforming Demonstration System

- FY99 Objectives
  - Demonstrate steam reforming in a microchannel reactor
  - Demonstrate high effectiveness, compact recuperation



- FY00 Objectives
  - Scale-up - 4 trains @ 4-20 kWe
  - High efficiency



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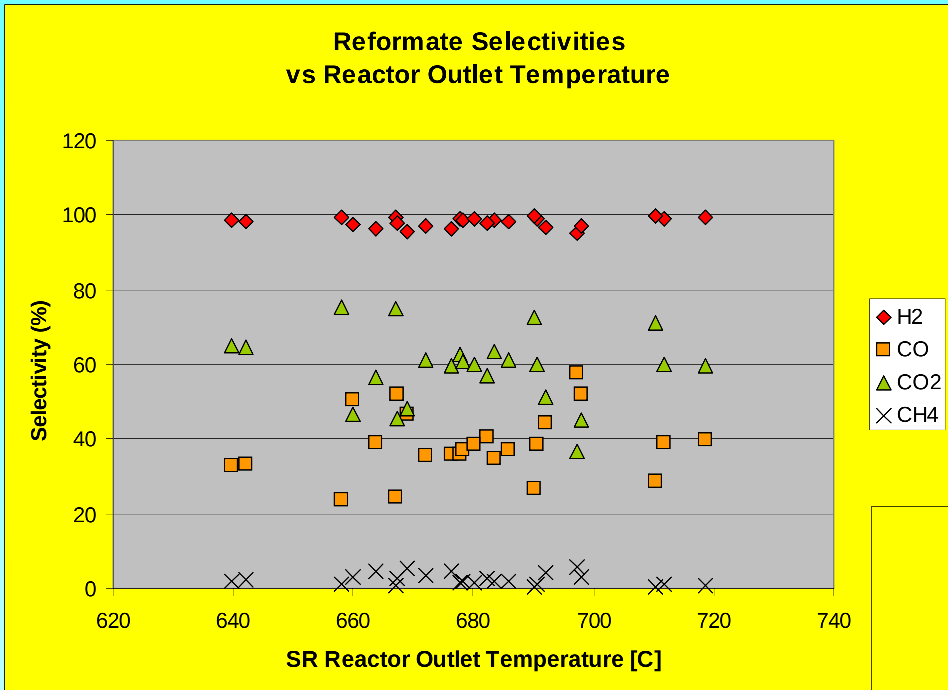
Microchannel Steam Reforming Reactor Testing

- Objectives
  - Obtain design data for next generation design
  - Demonstrate capacity / Validate power density progress
  - Characterize reactor performance for system modeling

- Statistically Design Experiment - 4-factor full factorial design
  - Reactant flow rates
    - Residence time
    - Steam to Carbon (3:1 to 12:1)
  - Heat transfer - combustion gas flow rate and temperature
    - Reactor temperature
    - Capacity rate ($\dot{m}\, C_p$ of combustion gas stream)
  - Measured conversion and selectivities

Microchannel Steam Reforming Reactor Testing

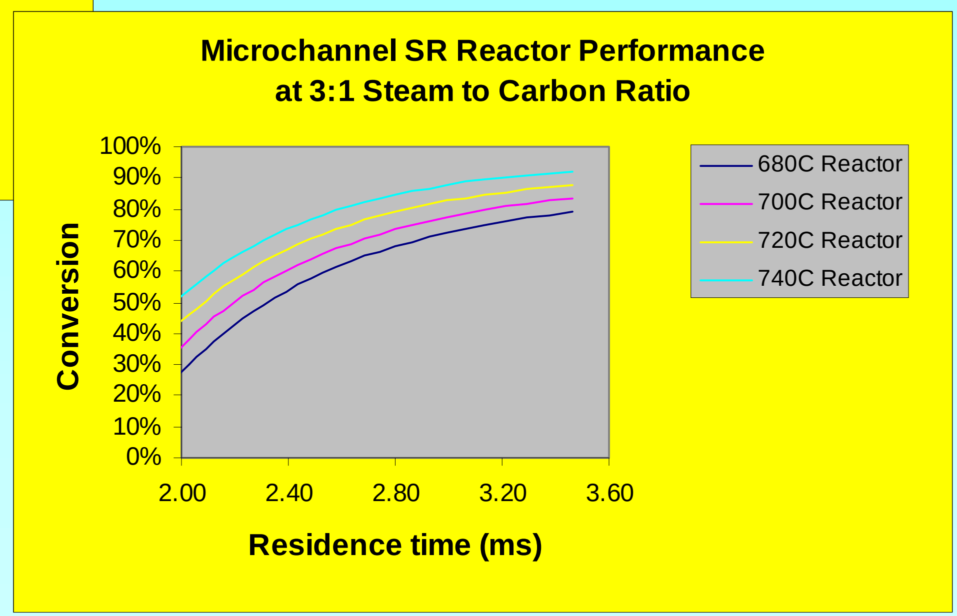
First Generation Reactor Experimental Data



- High H_2 selectivity
- Low methane slip
- Some High Temperature Water Gas Shift Reaction

Data is for a wide range of reaction conditions (temperature, steam:carbon ratio, residence times, etc)

- Data statistically fit to correlations for predictive modeling of conversion and selectivity



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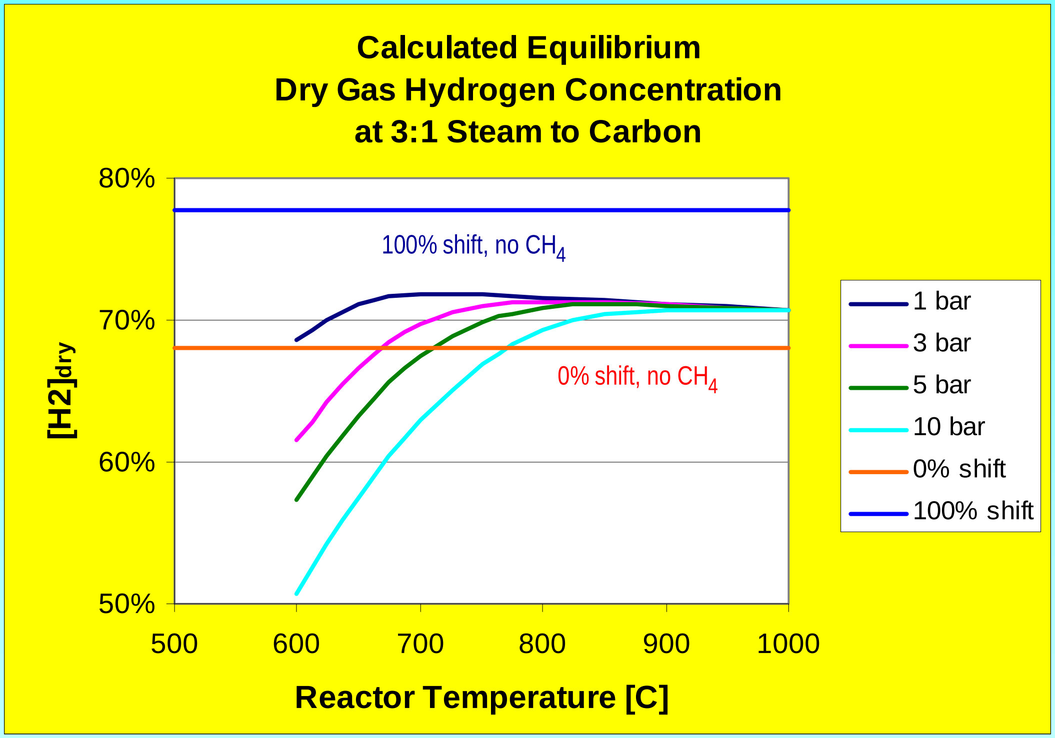
Steam Reforming
High Temperature Water Gas Shift



- High temperature shift gives >100% yield.
- Methanation reduces yield at lower reactor temperature and higher pressure.
- Higher steam to carbon increases yield and shifts maximum to lower temperature.

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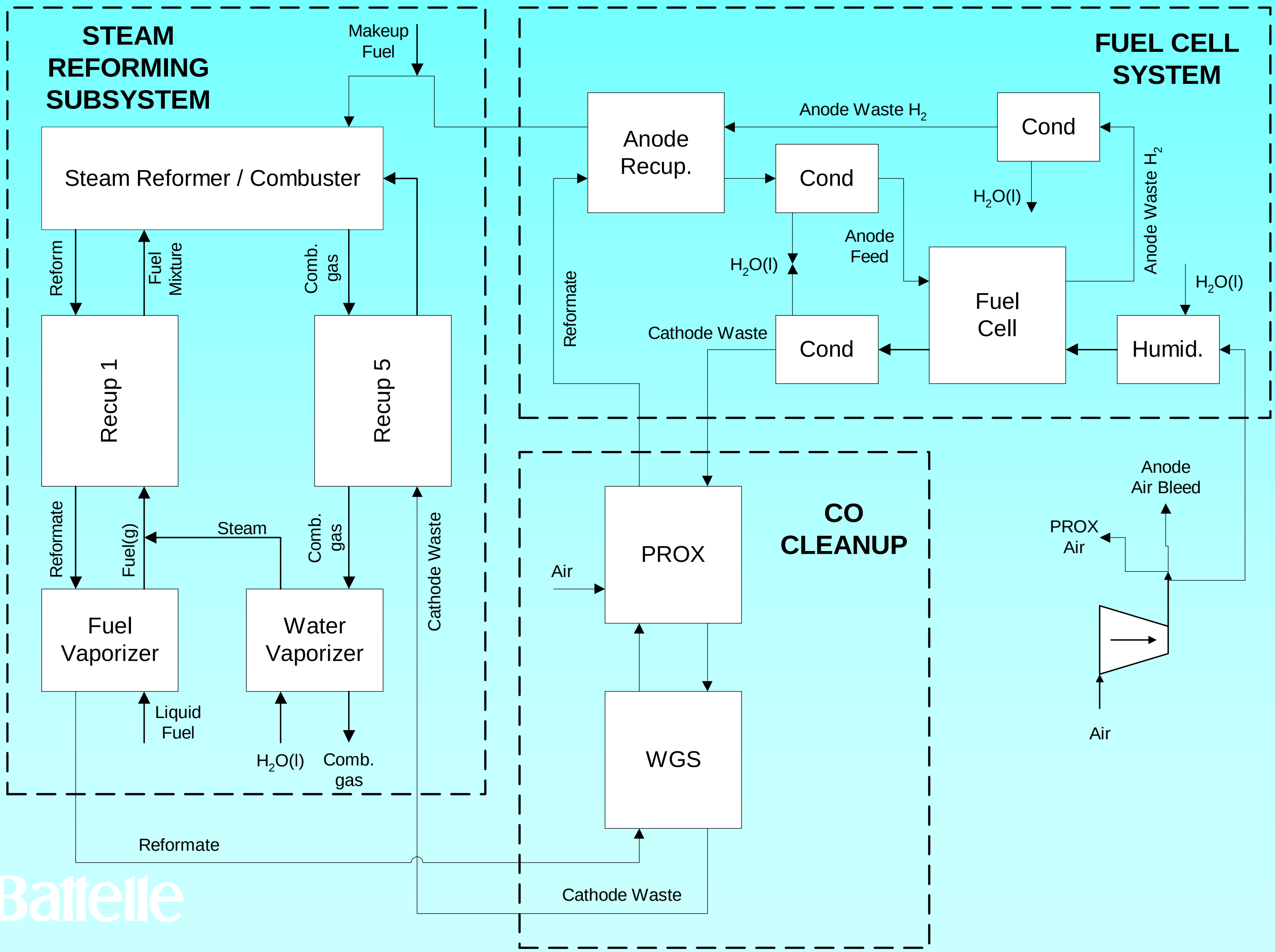
Fuel Cell / Steam Reforming Fuel Processor



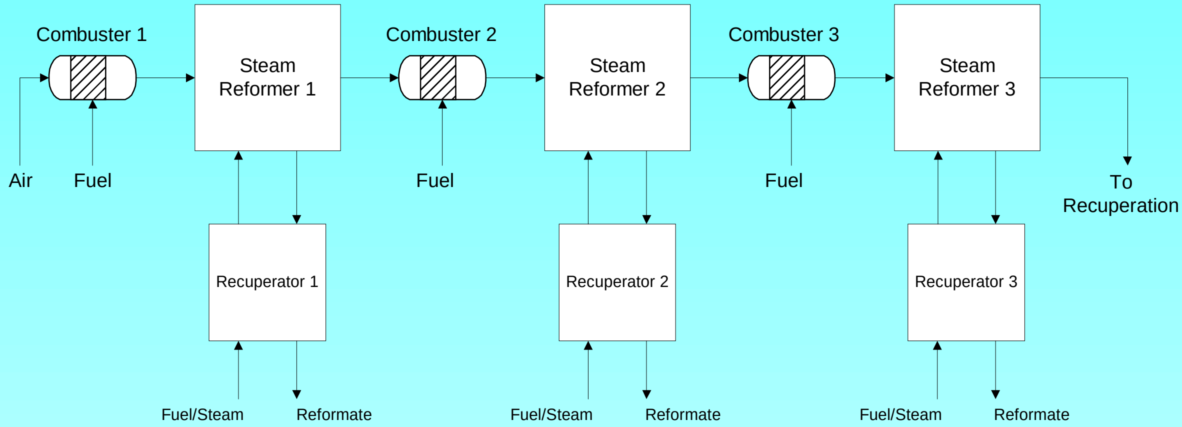
System Efficiency

- Energy Efficiency
  - > 43% overall system (including compressor)
  - 84% fuel processor efficiency (Steam reformer and CO cleanup, anode waste free)
  - at 60% fuel stack efficiency (w/o compressor, requires 0.84V & 85% utilization)

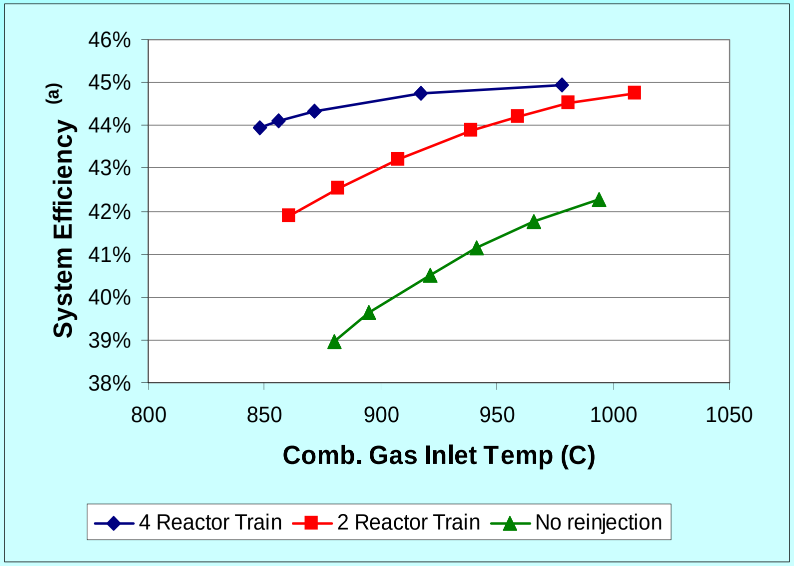
- Steam Reformer Assumptions
  - 700°C Operating Temperature
  - 90% Fuel Conversion
  - Equilibrium Carbon Selectivity
- Unreacted fuel burned in combustor (?)
  - Facilitated by alternative reformate treatment options (see poster)
- Water balances at 54°C heat rejection temperature

High Temperature Combustion

Combustion Gas Reinjection Scheme



- **Enabled by modularity of microchannel architecture**
- **Potential Benefits**
  - Lower combustion temp - stainless steel construction
  - Higher reactor temperature - smaller reactor / more shift
  - Lower combustion flow - smaller heat exchangers
  - **Higher system efficiency**



(a) Assumes 54% fuel cell efficiency

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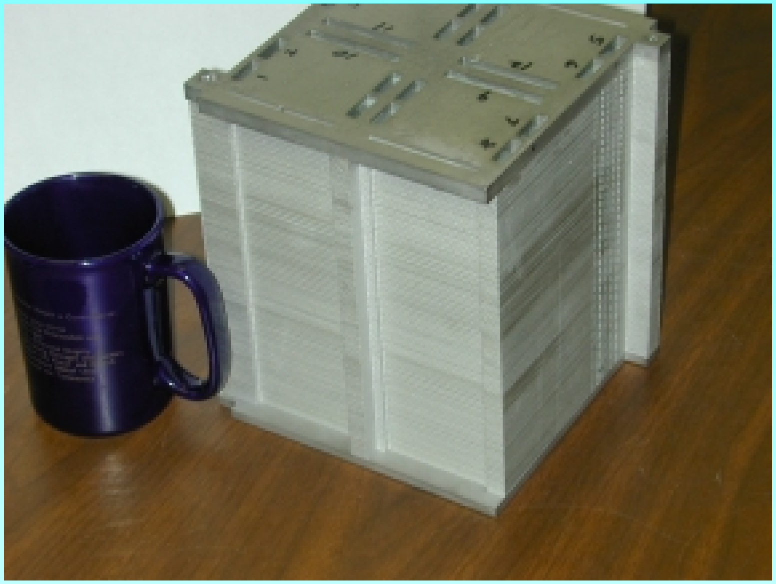
10 kWe Steam Reforming/High Temperature Shift (SR/HTS) Reactor System

Objectives:

- Scale-up capacity from ~1 kWe to 10 kWe

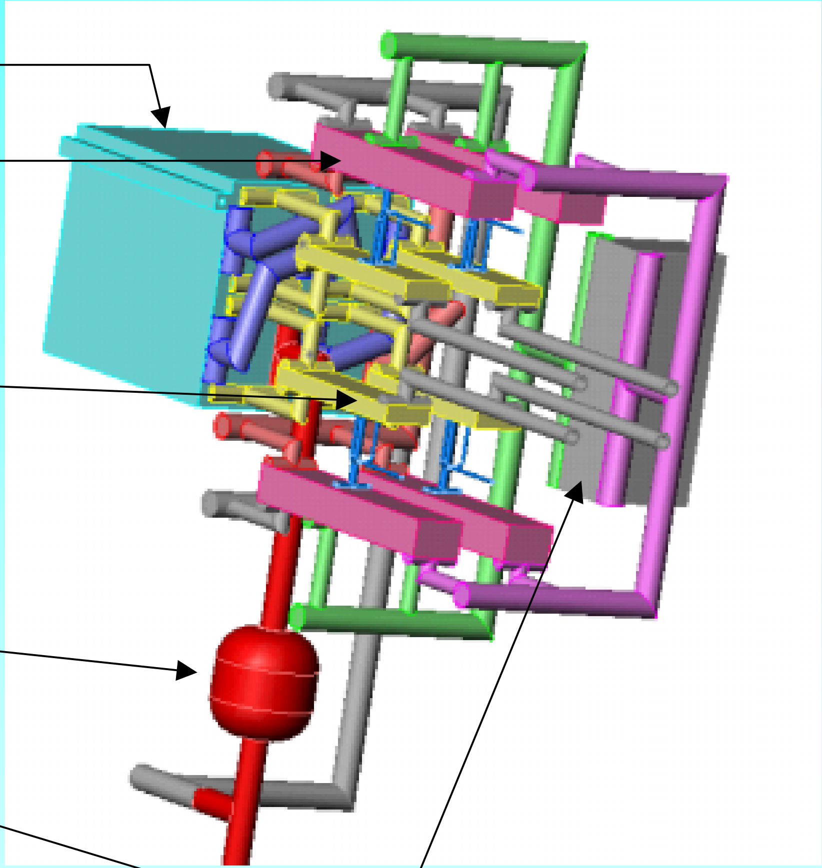
- Enable Energy Efficient Operation



Bonded Stack for 10 kWe Reactor

Integrated 10 kWe SR/HTS System

- 4-Cell Steam Reformer
- 4X Combustion Air Recuperators / Water Vaporizers
- 4X Reformate Recuperator / Fuel Vaporizer / Water Preheat
- Combustor
- Air Preheater



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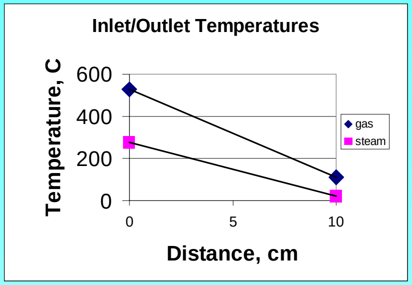
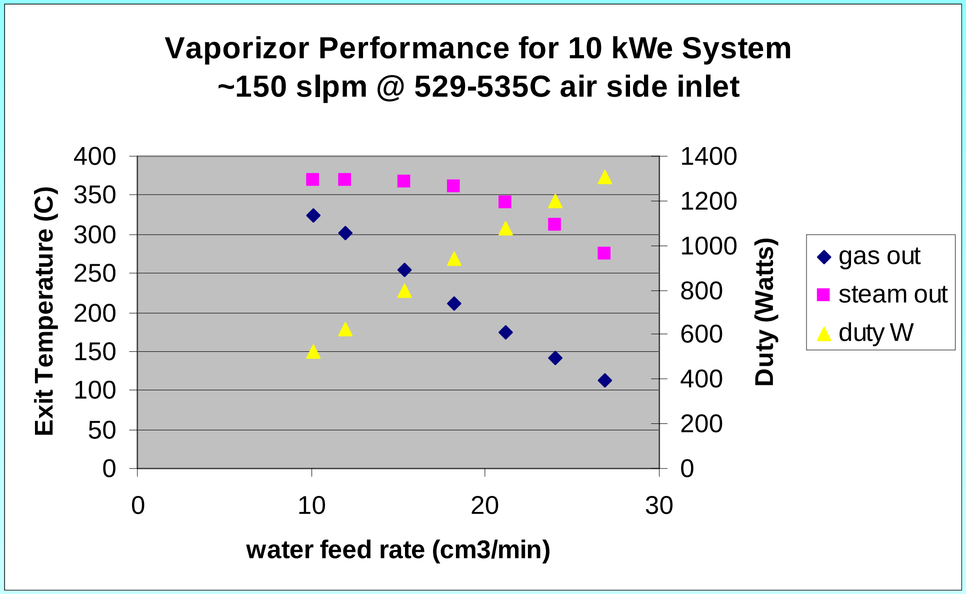
Multi-Stream Combustion Gas Exchanger

Combustion Exhaust from Reactor is used to:
- Provide Preheat for Combustion Air
- Vaporize Water



Bonded Stacks for Integrated Combustion Gas HX (4 required)



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Reformate/Reactant Recuperator Test Unit

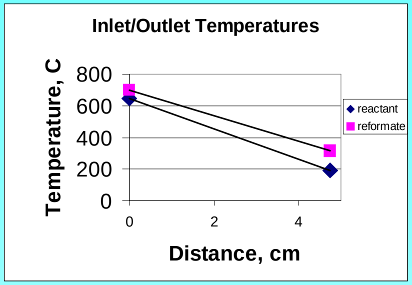
Expected Performance At Design Condition

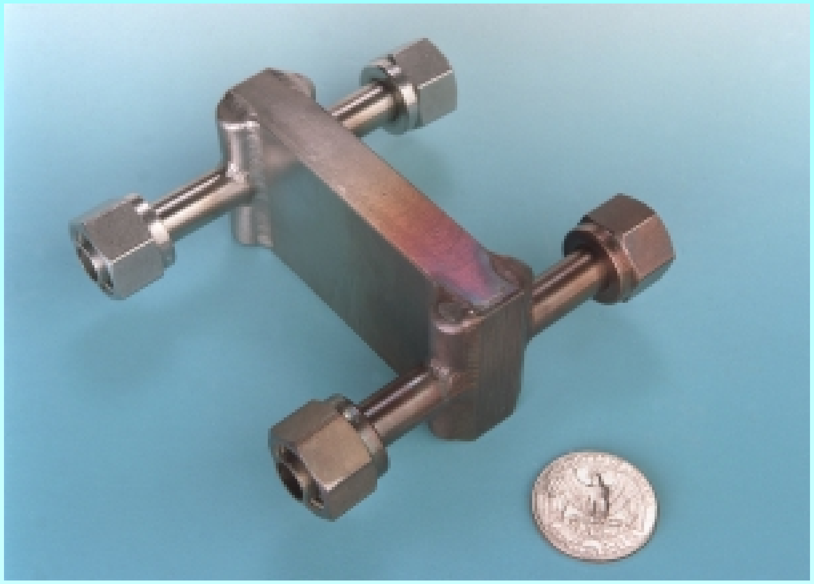
Effectiveness = 89%

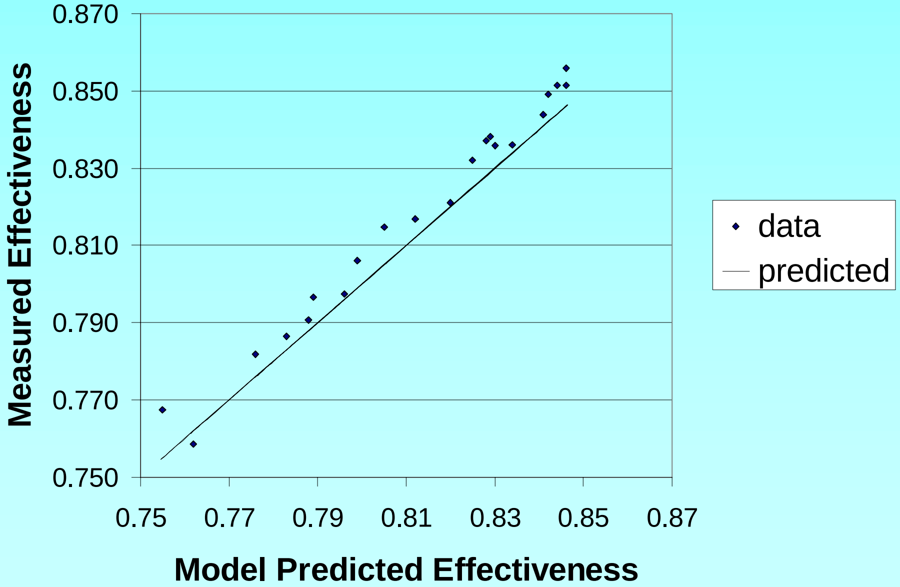
Pressure Drop = 1.1 psi (reformate side)

Total Volume = 37 cm^3 (excludes tubes)

Duty = 897 W





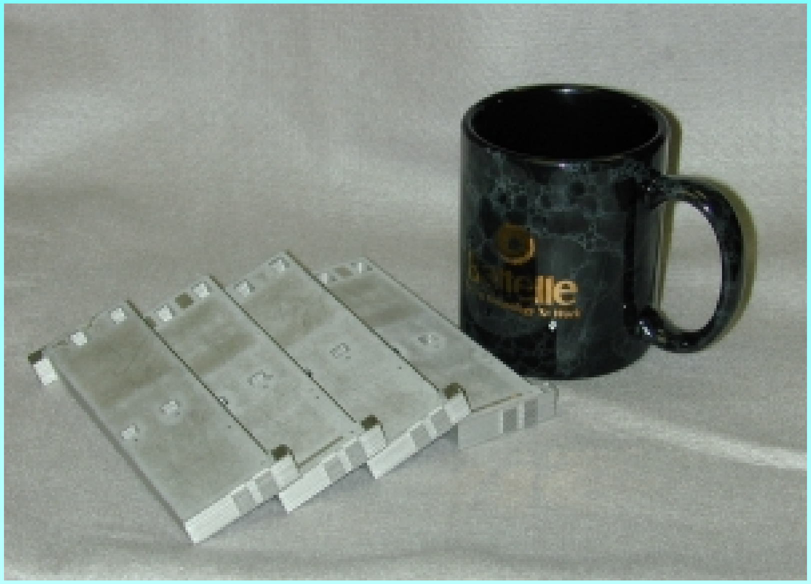


N_2 Test Data vs Model

Multi-Stream Reformate Exchanger

Heat in Reformate Product is used to :

- Preheat Vaporized Fuel and Steam (90% effective)
- Vaporize Fuel
- Preheat Water to Vaporizer



Bonded Stacks for Integrated Reformate Exchanger (4 required). Units designed to eventually mate with combustion gas exchanger to form single exchanger unit.

Condensers / Air Preheat Exchanger

Air Preheat Exchanger:

- Recover low quality heat from vaporizer exhaust
- At design conditions, duty = 3216 W, effectiveness = 90%.
- May not be required after integration.
- Eventual non-stainless construction.

Microchannel Condensers:

- Not part of Steam reforming subsystem.
- Provides cooling and removal of water from reformate prior to analysis/ venting.

Bonded Microchannel Condensers

Development Status Compared To Targets

For a 50 kWe fuel processor/fuel cell system...

	DOE/PNGV Status Fuel Proc Sys	DOE/PNGV 2004 Target Fuel Proc Sys	PNNL Microchannel Steam Reformer 2000 Achievable	PNNL Microchannel Steam Reformer 2004 Goal
Overall System Efficiency	30% [a]	48%	39-41%	47-49% [e]
Fuel Processor Efficiency	70% [a]	80%	83-85%	83-85%
Fuel Processor Size (Liters)	166 [a]	66.7	30 - 15 [b]	< 8 [d]
Fuel Processor Weight (kg)	166 [a]	66.7	180 - 90	< 30
Fuel Processor Cost ($)	3000 [a]	500	~ 3000 -1500 [c]	< 200 [c,d]

[a] As of January 2000
[b] Includes improvements to current demonstration unit
[c] Based on cost of bonded unit only (no catalyst costs)
[d] Requires improvements to catalyst performance and/or manufacturing methods
[e] Depends upon improvements to fuel cell performance and balance of plant hardware

Plans

- Demonstrate highly efficient operation of microchannel reformer at 10 kWe
- Advance to transportation fuels (e.g., methanol, gasoline, diesel, and middle-distillates)
- Catalyst development critical (durable, tolerant of poisons such as sulfur); Battelle Memorial Institute currently investing private funds to address catalyst issues
- Manufacturability/cost reduction investigation
- Integration of all components of a complete fuel processor into a single device is an ultimate goal
- Increase external interactions

Interactions

- Tested ANL catalysts developed for autothermal reforming; collaborating on overall system performance modeling
- Plug Power – propose to test integrated fuel reformer with PEM fuel cell stack
- McDermott – provide heat exchangers for testing and evaluation
- Epyx – tested fuel vaporizer (1999)
- Active participation at national symposia, technical publications

Summary

- Current microchannel fuel reformer system provides higher capacity and greater efficiency than earlier design
- Steam reformer subsystem consists of a 4-cell reformer, multi-stream recuperative heat exchangers and steam/fuel vaporizers
- High hydrogen selectivity, low methane slip, and some high temperature water gas shift obtained
- Approach expected to meet PNGV targets for efficiency and size; improvements needed to meet weight and cost targets

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