Fore Court Fuel Processing:
Micro-Channel Steam Reforming of Natural Gas for Distributed Hydrogen Production

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Project ID # FCP26

This presentation does not contain any proprietary or confidential information

Overview

Timeline

- Project start date 10/1/05
- Project end date TBD/2010
- Percent complete ~50% FY05

Budget

- Total project funding
  - DOE share $400K
  - Contractor share NA
- Funding received in FY04=$0K*
- Funding for FY05=$400K

*on-board reforming FY04 funding $800K

Barriers

- Barriers addressed
  - Technical Target: Production Efficiency
  - Barrier: Fuel Processor Capital Cost

Interactions

- Battelle/UDLP/NAC – Bradley Fuel Cell APU
- GTI – Superboiler Economizer
- DOE/ NA-22 National Security Project – Light-weight, cryrogenic, micro-channel recuperator
- Idatech – vaporizer for evaluation
- U.S. Air Force –application of reformer technology to SOFC based UAV propulsion
- Velocys – Discussions related to fabrication of laminated micro-channel structures.

Objectives

Develop thermally efficient/low capital cost system for distributed hydrogen production from natural gas.

- Adapt the micro-channel steam reformer technology, initially developed for on-board reforming of gasoline, to distributed steam reforming of natural gas.
- Demonstrate at small scale (5 kg/day), a compact, efficient, integrated hydrogen production system including:
  - thermally integrated micro-channel steam reformer
  - conventional high-temperature WGS reactor
  - copper palladium membrane separator for H_2 purification
  - combustor utilizing membrane raffinate to heat reformer/vaporizer
- Provide basis for initiating evaluation of reduced-cost manufacture of micro-channel hardware for 1500 kg/day system.
- Advance technology through interactions.

Approach

- Adapt Reformer: on-board gasoline to fore-court natural gas. Design factors change:
  - Pressure 200 psi vs <50 psig
  - Less critical factors - startup time, startup energy, weight, volume
  - More critical factors - thermal efficiency, system durability
- Retain micro-channel design concept:
  - rapid heat and mass transport
  - small quantity of highly active catalyst
  - efficient heat transfer enabling tight thermal integration
  - cost reduction through reduction in overall system size and materials.
- Design for 2-pass reformer system
  - Increased temperature change on combustion stream passing through the reformer reduces air flow and improves efficiency
  - Reacting reformate stream is recuperated between reforming stages
- Fabricate/demonstrate compact system for 1000 hour test.

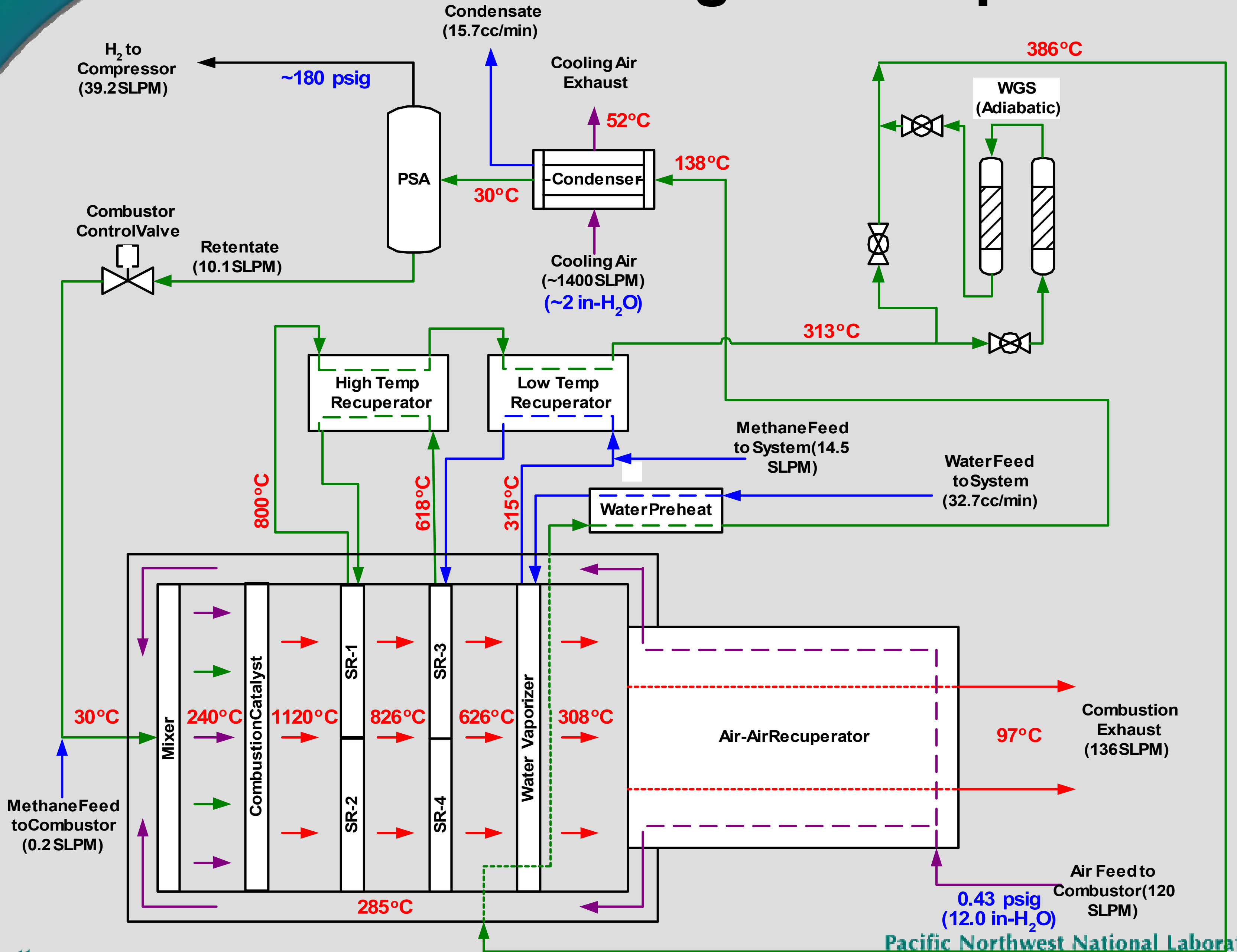
Technical Accomplishments

- Mass and energy balance simulations completed for two system flowsheets.
- Iterated on flowsheet calculations using actual hardware designs to arrive at efficient flowsheets consistent with actual hardware performance.
- Target efficiencies for the two flowsheets calculated.
- Designed micro-channel components in the steam reforming system.
- Fabrication of individual components underway.
- Numerous interactions underway.

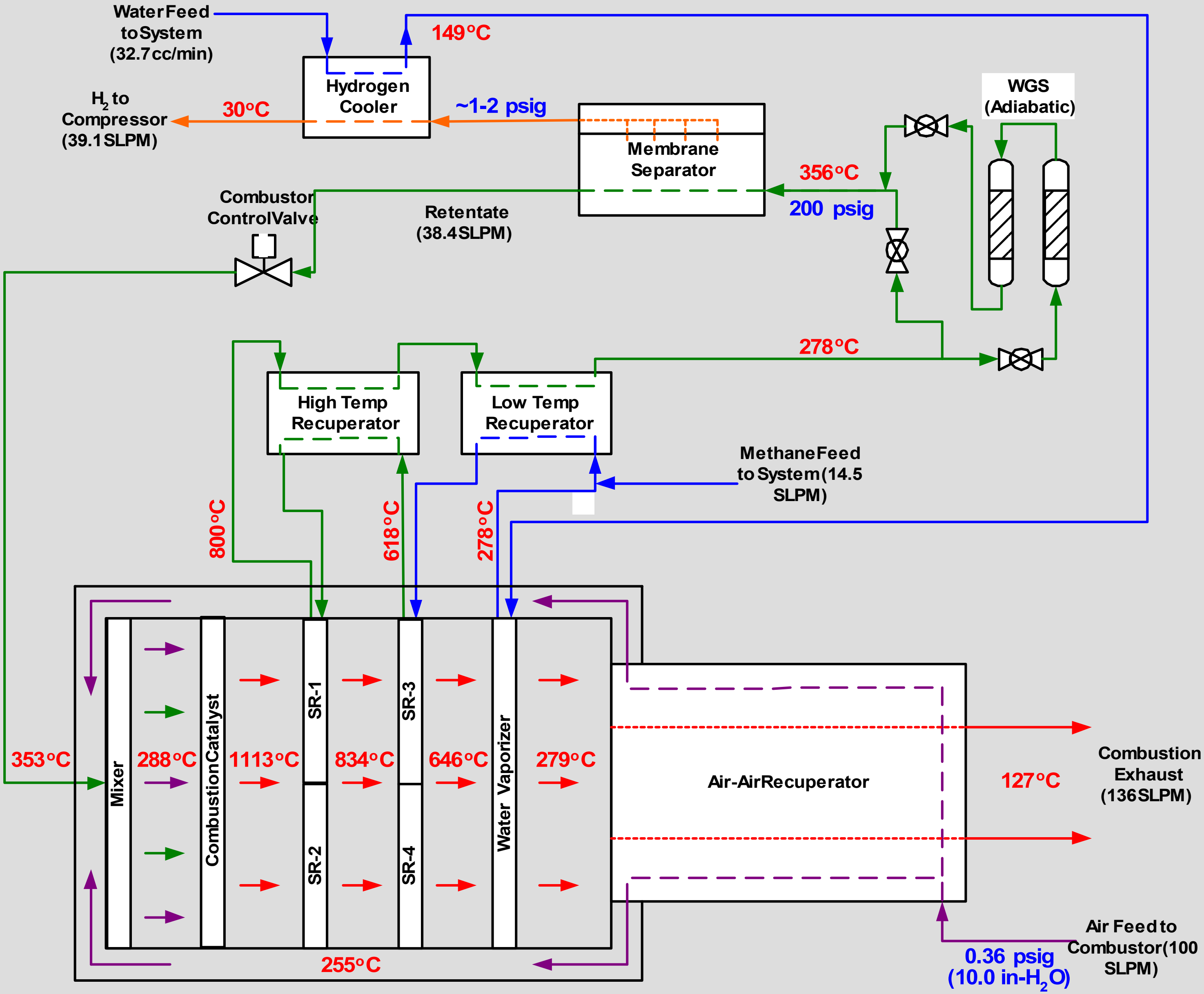
Flowsheet Calculations for Steam Reformer Using Membrane / PSA Based Separation

- Purpose
  - Provide flowsheet to be used in 5 kg/day demonstration
  - Provide input to thermal design of heat exchangers
  - Assess benefit of including high-temperature WGS reactor
  - Assess potential system efficiency relative to 2010 target of 80%
- Assumptions
  - Initially simulated on methane feed to match planned demonstration
  - Input methane at 200 psig without additional compression
  - Assume 90% hydrogen recovery at separation with adequate purity
    - Membrane designed to accomplish this for test
    - Compare PSA assuming it can meet similar performance level
  - Set steam:carbon ratio at 2.8:1
    - Prevents equilibrium carbon formation in membrane flowsheet
- Calculation Approach –ChemCad flowsheet software

Flowsheet Using PSA Separation



Test System Flowsheet (Membrane)



Potential Energy Efficiency Conclusions/Improvements Identified

- Including high-temperature WGS found to be beneficial
  - increases total system efficiency by 1.3%
  - Allows use of reduced reformate temperature (800°C vs 865°C)
- Shift reaction beyond an adiabatic high-temperature shift was found to have no benefit on efficiency.
- Natural Gas Compression/High Pressure Reforming
  - Hydrogen flow is ~2.7X greater than natural gas flow
  - With PSA flowsheet, efficiency improves 4% if compression to 40 atm is achieved on natural gas instead of hydrogen.
  - Tradeoff is higher pressure and temperature in reforming section and higher pressure in PSA vessels.
  - For current effort, feed is assumed at 200 psi and hydrogen is then compressed to higher pressure.

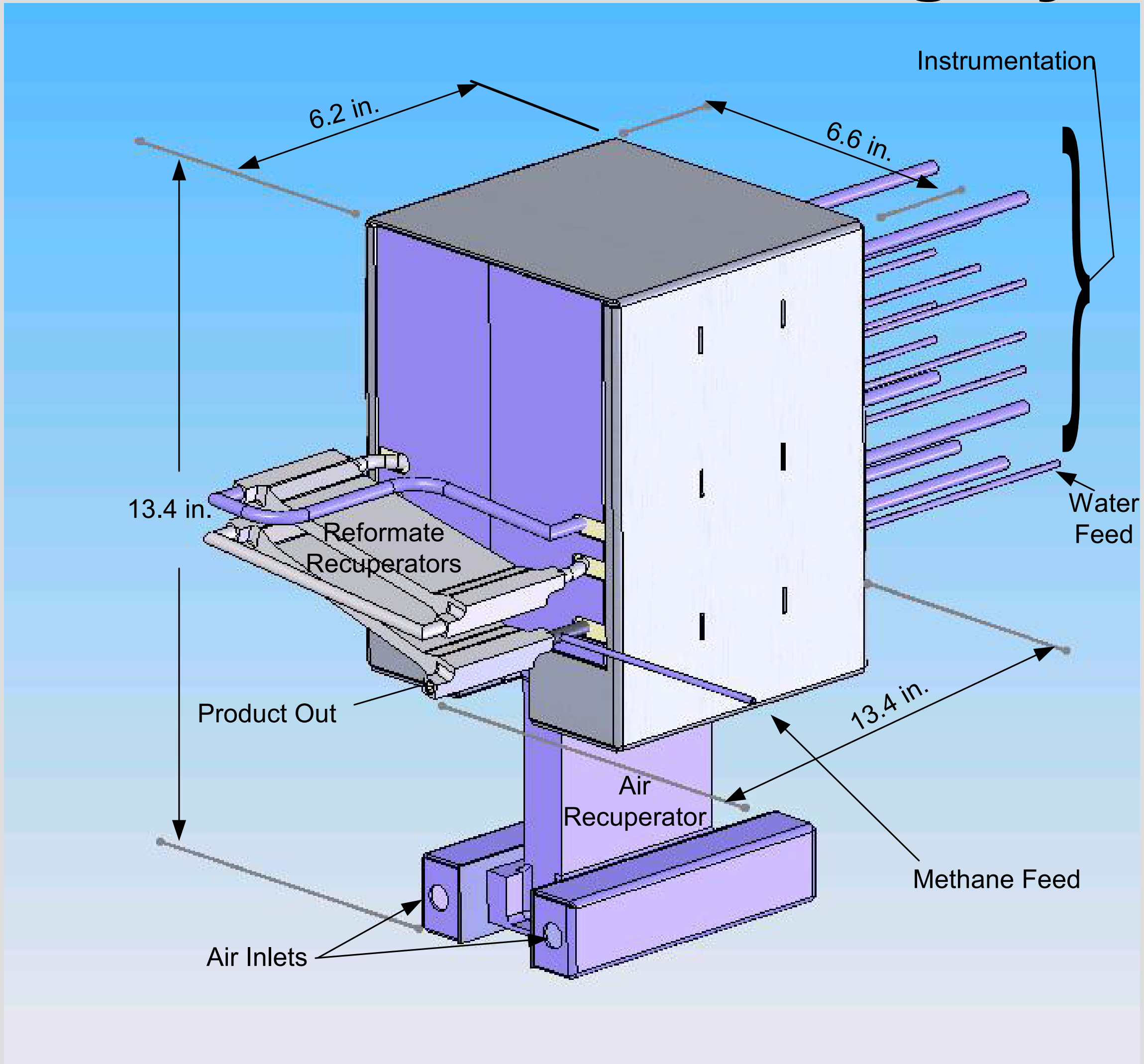
Calculated Flowsheet Efficiencies

- 90% recovery membrane based system
  - 81.1% (LHV H2/LHV fuel feed)
  - 78.4% (LHV H2/(LHV fuel + parasitic + compression to 180 psig))
- 90% recovery PSA based system (compression not req'd)
  - 80.3% (LHV H2/LHV fuel feed)
  - 80.0% (LHV H2/(LHV fuel + parasitic)
- Comparison point:
  - DOE 2010 production efficiency target of 80%

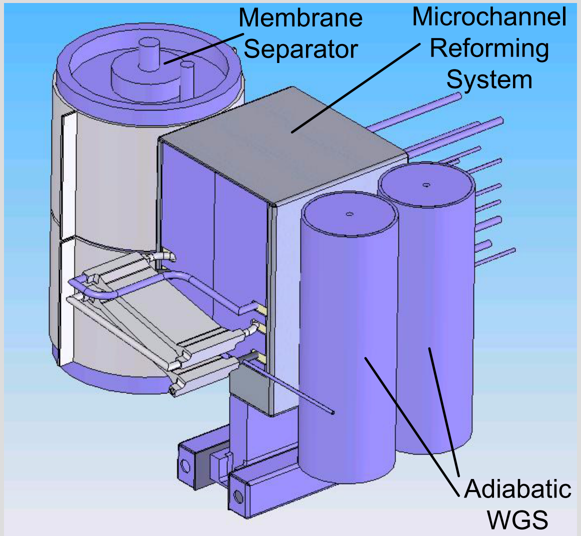
Flowsheet Comparison: PSA separation and Membrane Separation

- Both flowsheets provide efficiency estimates (PSA 80.0%, membrane 81.0%) close to the 2010 target of 80%.
- Accounting for compression of product hydrogen from the membrane to 180 psig reduces membrane system efficiency to 78.4%.

Layout of Experimental 5 kg/day Reforming System



Left: Microchannel Reforming System
Below: Reformer Integrated with Fe-Cr WGS reactor and Cu-Pd membrane separator. (both obtained commercially)



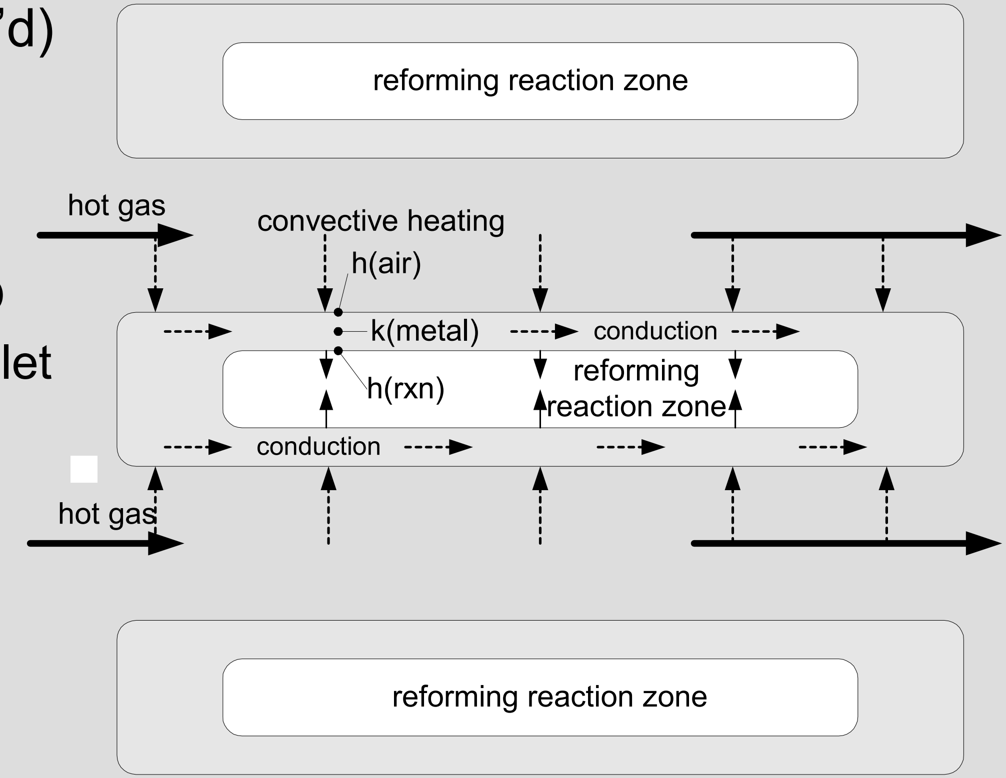
Estimated Recuperator Performance
(important factor in achieving high efficiency)

- Reformate Recuperators
  - Duties 346 W/716 W for high/low temperature units respectively
  - Effectiveness 91-92%
  - Mass (inconel) ~ 484 g each
- Air Recuperator (1)
  - Duty 500 W
  - Effectiveness ~90%
  - Mass (316L stainless) ~1560 g core/ 1898 g including header connections
  - Pressure drop 3.0 in. H_2O hot side/ 1.9 in. H_2O cold side

Microchannel Reformer Panel Reactor

- Reforming Reactor Panels (2 high/2 low temperature req'd)
  - Mass ~280 g ea. (Inconel)
  - High Temp Duty=551 W ea.
  - Low Temp Duty =353 W ea.
  - Total Air Side dP~1.2 in. H_2O
  - Tolerant of high (~1100°C) inlet temperatures.

Reforming Reactor Panel

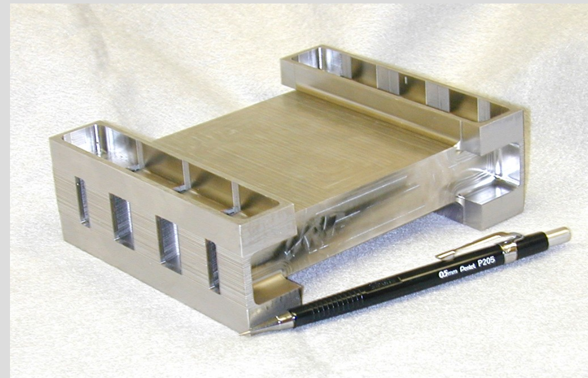


Cross Section of Low-dP Reformer

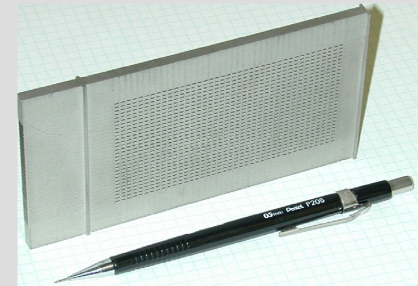
(Not to scale. Reforming flow is into the plane of the diagram)

Schedule for Test System

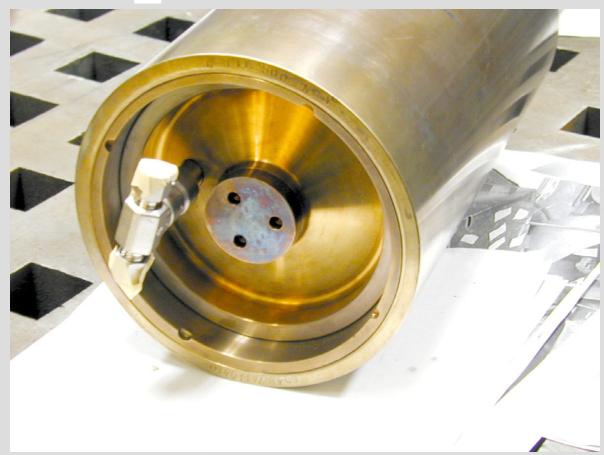
- Components completed
  - Water Vaporizer
  - Air Recuperator
  - WGS Reactor
  - Reforming Catalyst
  - Combustion Catalyst
- Complete by Mid-May
  - Membrane Separator
  - Reforming Reactor
  - Reformate Recuperators
  - Combustion Mixers
- Early June
  - System assembly and instrumentation
- Mid-June – System Testing



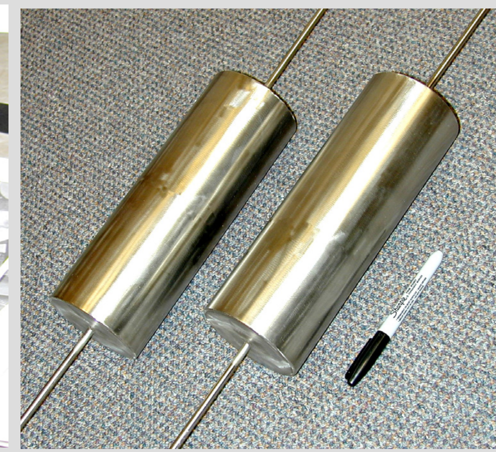
Air Recuperator



Water Vaporizer



Cu-Pd Membrane Separator

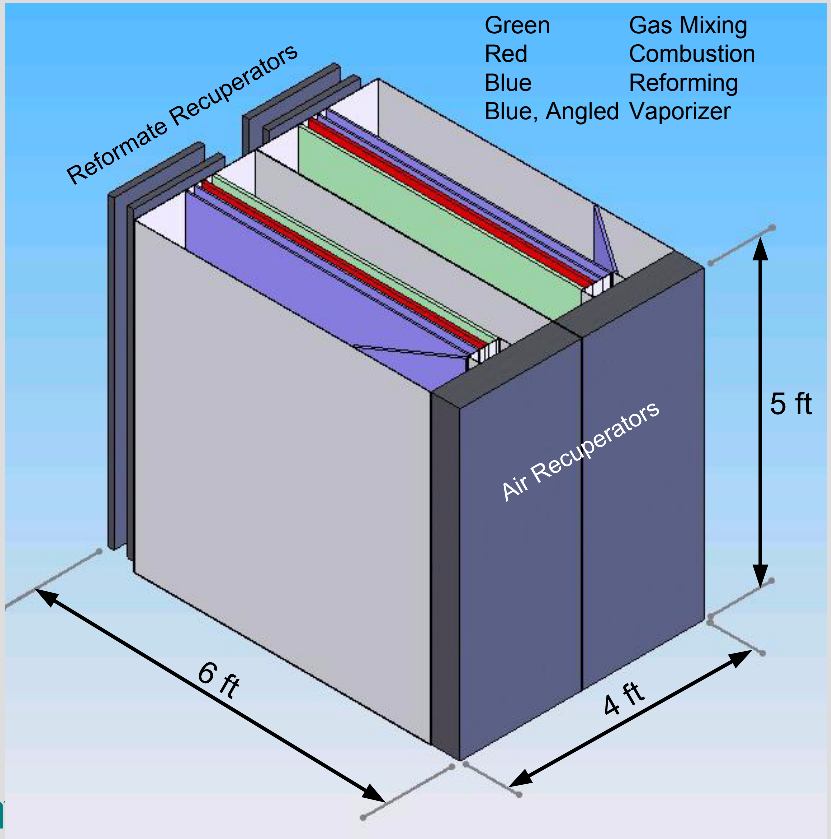


WGS Reactor (Fe-Cr catalyst)

Scale-up of Reformer to 1500 kg/day

Conceptual Full-Scale Reformer

While only conceptual, this illustrates the system will fit within the footprint of an existing station.



Full Scale Raw Material Costs

Value of Rh metal in reforming catalyst ($63.60/gram) is ~$25,000

Value of Inconel (~$17/lb) is on the order of $23,570

- Value of stainless steel $2.31/lb is on the order of $2870

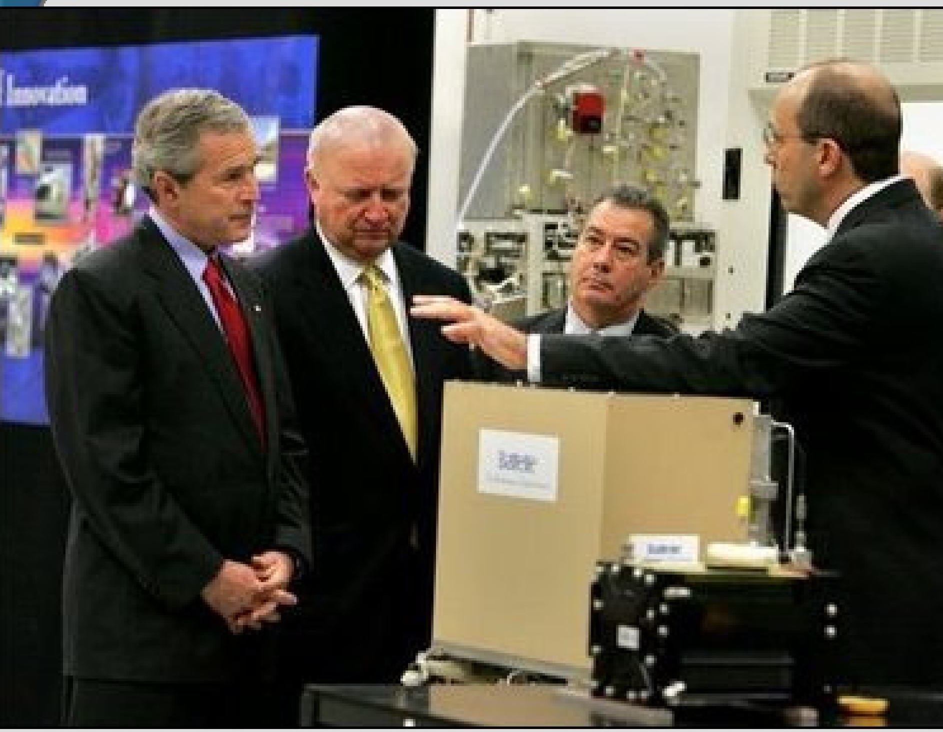
Total=$51440

Conclusion: Key to capital cost feasibility will be in the costs added during manufacturing, not the underlying raw material costs.

Interactions: Bradley Fuel Cell Auxillary Power Unit (APU)

- Participants
  - PNNL/Battelle Northwest
  - Battelle Memorial Institute
  - United Defense Limited Partnership (UDLP)
  - US Army National Automotive Center (NAC)
- Objective: Develop and demonstrate a prototype fuel cell power system for the Bradley fighting vehicle to enable silent watch.
- Key enabling technology: Highly compact reforming reactor and heat exchangers (EERE-developed). Adapted for synthetic JP-8.
- EERE loaned micro-channel water vaporizers and combustion mixers for testing within systems.
- Integration of fuel processor with membrane separator similar to integration approach in current project.

Interactions: Bradley APU (continued)



President Bush and Energy Secretary Sam Bodman are briefed on the Bradley Fuel Cell APU unit during a March 9th 2005 visit to Battelle Memorial Institute in Columbus Ohio

The fuel cell APU is shown installed in a bustle box on the back right quadrant of the Bradley Fighting Vehicle during the Association of the US Army Winter Symposium, held in Feb 2005.

Reforming Efficiency Data on Bradley APU Steam Reformer

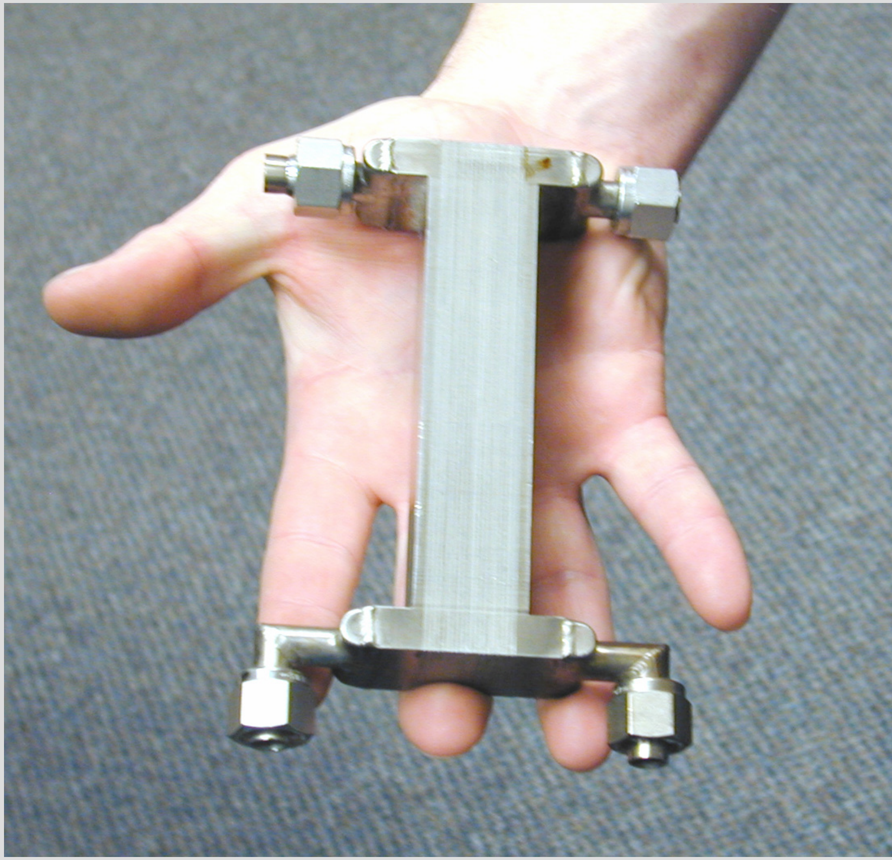
- The Bradley APU and test system are of similar scale.
- The Bradley APU Project demonstrated the efficacy of an integrated micro-channel reformer/membrane hydrogen production system.
- Test data on Bradley APU shows an efficiency for hydrogen generation and purification of 67% (LHV pure H_2 produced/ LHV total fuel fed).
  - Execution speed was valued over system efficiency.
  - Efficiency of 67% on prototype is viewed as a positive indication with respect to ability to achieve 80% efficiency in the natural gas reformer.
- Several design factors are included to improve the current test system efficiency relative to Bradley APU including:
  - Double pass reforming reactor
  - Lower S:C ratio due to higher H:C ratio of fuel
  - Higher effectiveness design for reformate recuperators
  - Reduced heat loss due to design changes and improved insulation.

Interactions: GTI/Cleaver-Brooks: Boiler Economizer

- Participants
  - PNNL
  - Gas Technology Institute
  - Cleaver-Brooks
  - Funding via DOE OIT "superboiler" program
- Objective: Fabricate and deliver for testing, a highly efficient economizer for a 3MM BTU/hr fire-tube boiler.
- The micro-channel heat exchanger technology, developed on the EERE program, was adapted to the economizer application.
- Unit is currently undergoing testing at GTI

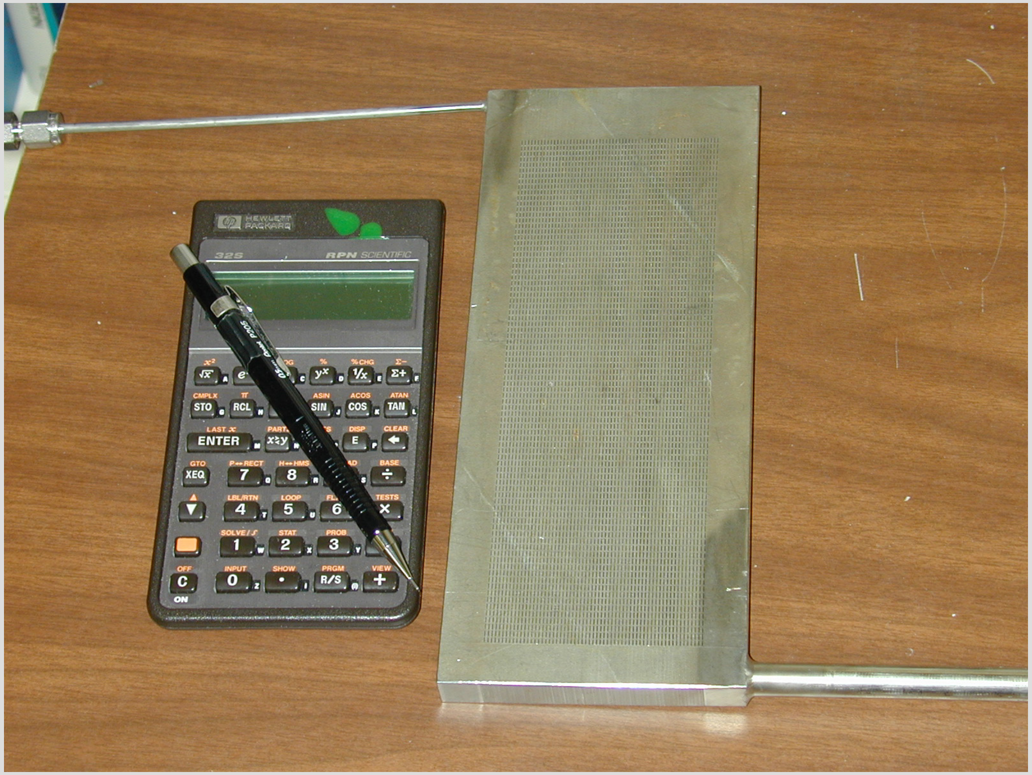
Interactions: DOE/ NA-22 National Security Project

- Project required a highly-efficient yet low thermal mass gas phase recuperator to operate at near liquid nitrogen temperatures.
- EERE program loaned an existing recuperator built to support reforming test activities for evaluation in system.
- Superior Performance: Test results indicate higher recuperation efficiency with ¼ the mass of a commercial heat exchanger custom-designed for the application.



Interactions: Idatech

- Microchannel vaporizer, originally built as an experimental prototype for the EERE program, was loaned to Idatech for testing and evaluation.
- The catalyst for hydrocarbon reforming is being provided for testing and evaluation. The catalyst was developed as a Battelle corporate investment in support of the EERE funded reforming project.

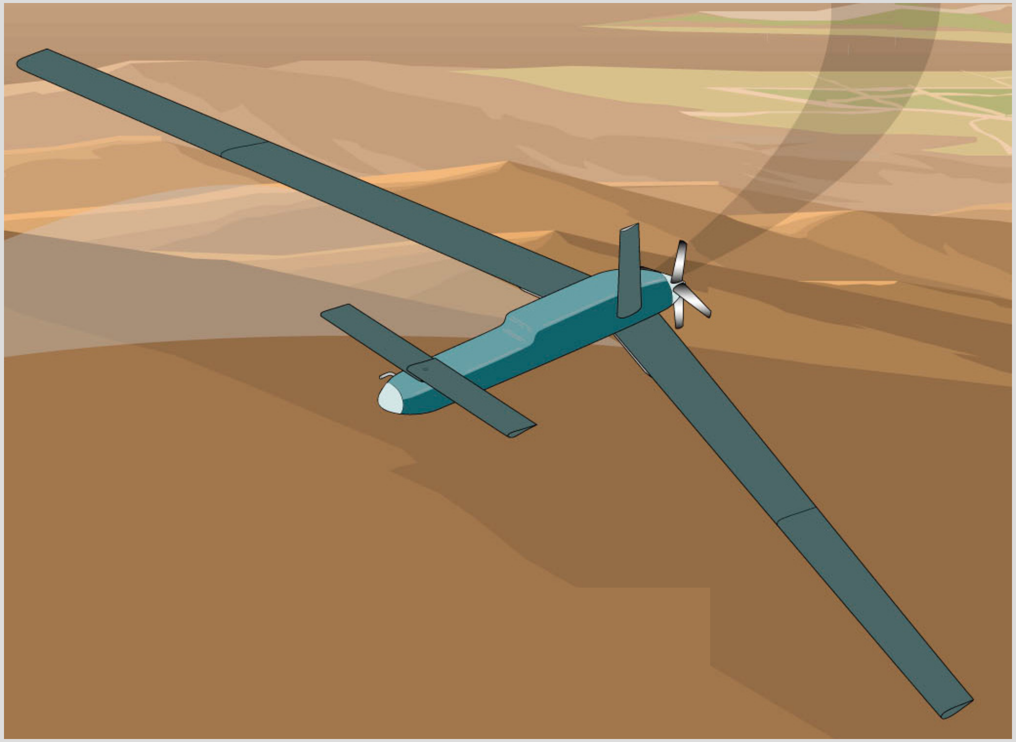


The water vaporizer loaned is shown above. This vaporizer nominally is sized to vaporize ~2cc/s of water for a thermal duty of approximately 6 kW. Air side dP<2.5” H_2O

Interactions: U.S. Air Force

- In discussions with air force to adapt reforming technology to an SOFC system for UAV propulsion power.

- Key Objectives
  - Minimize weight
  - Minimize volume
  - Maximize efficiency



End result: Extend the flight duration beyond that achievable via conventional technology.

Future Work

- Remainder of FY05 –
  - Complete system fabrication.
  - Conduct 1000 hour test.
  - Demonstrate thermal efficiency.
- FY06
  - Evaluate scaleup to 1500kg/day system
  - Explore fabrication techniques and/or design changes to reduce cost for producing laminated micro-channel structures.
  - Estimate fabrication cost of 1500 kg/day systems when produced in a quantity of 100's/yr.
- Decision point at end of FY06: Down-selection of research for distributed hydrogen production from natural gas.

Hydrogen Safety

The most significant hydrogen hazard associated with this project is:

The most significant hazard is the potential for a failure of the reforming reactor during operation at elevated pressure (200 psig). Potential failure mechanisms include high temperature creep rupture of the reactor structure, corrosion or some combination of these mechanisms. If a failure occurs in the reactor, hot reformate would be vented into the hot combustion gases, would likely combust, and cause high temperatures downstream from the reactor. The loss of pressure would result in an initial control system response to increase steam and methane flows as the system attempt to maintain the system pressure. In addition, the loss of pressure would halt hydrogen permeation, throwing the system heat balance further towards the positive side. If not corrected, the condition would increase system temperatures to the point were downstream components could fail due to softening and/or melting.

Hydrogen Safety

Our approach to deal with this hazard is:

- **Design to prevent failure.** The unit is planned to be operated at 200 psig with a reformate temperature of 800C for a 1000 hour test run. The structure of the reactor is designed to withstand 220 psig at a temperature of 950C over a 2000 hour creep time with a safety factor on allowable stress of 3 (i.e. at 220 psig and 950C a pressure of 3x220=660psig would be expected to cause failure within 2000 hours). Also, a pressure relief valve is provided to prevent excessively high pressures from occurring.
- **Contain high temperature gases.** The duct containing the reactor is insulated inside to isolate metal structure from temperature of combustion stream.
- **Enable Rapid Shutdown.** If operating attended, the system provides an audible alarm if a variable is outside normal range. A single button shutdown relay is provided for emergency shutdown. If operating unattended the control system will automatically shut the system down in response to a temperature or pressure drifting outside the acceptable range.
- **Prevent Inappropriate controller response.** Once at steady state, a clamp will be placed on the maximum fuel input rate to prevent inappropriate increases in response to loss of system pressure.