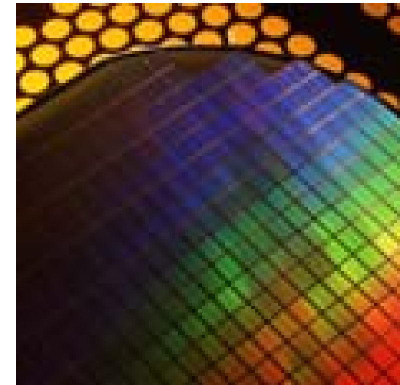
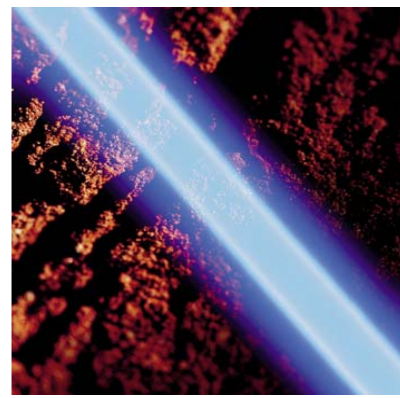
PRAXAIR

Low Cost Hydrogen Production Platform

Cooperative Agreement: DE-FC36-01GO11004
Project ID #: PDP5

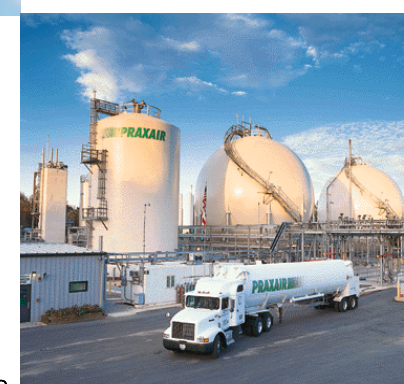


Timothy M. Aaron



Team

- Praxair - Tonawanda, NY
- Boothroyd-Dewhurst - Wakefield, RI
- Diversified Manufacturing - Lockport, NY



DOE Hydrogen Annual Review Meeting
May 16 - 19, 2006

This paper was written with support of the U.S. Department of Energy under Contract No. DE-FC36-01GO11004.

Praxair Hydrogen

- **Only U.S. hydrogen supplier in all sizes (cylinders to liquid to pipelines)**
  - First industry-financed liquid hydrogen facility (1959)
  - Six large LH_2 plants designed, constructed, and operated
  - Largest capacity single-train LH_2 production system (60 t/d)
  - Four LH_2 plants currently in operation
  - Smallest industrial SMR-based product line (HGS)
- **Over 1 billion SCFD capacity in 2006**
- **Current distribution network:**
  - Over 600 GH_2 and LH_2 customers
  - Over 300 miles of GH_2 pipeline
  - Fleet of liquid and compressed gas trailers
- **First PSA H_2 unit (over 300 designed and built)**

LCHPP – Program Goal

- **Low cost on-site hydrogen production**
  - Existing technologies (SMR)
  - Transportation and industrial (4.8 kg/h)
  - Approach DOE goal of $1.50 - $2.00 kg
  - Gas station capacity and size
  - Single skid
  - Easily installed
- **DOE barriers addressed (top 3)**
  - A. Fuel processor capital costs
  - B. Fuel processor manufacturing
  - C. Operation and maintenance (O&M)

Project Timeline

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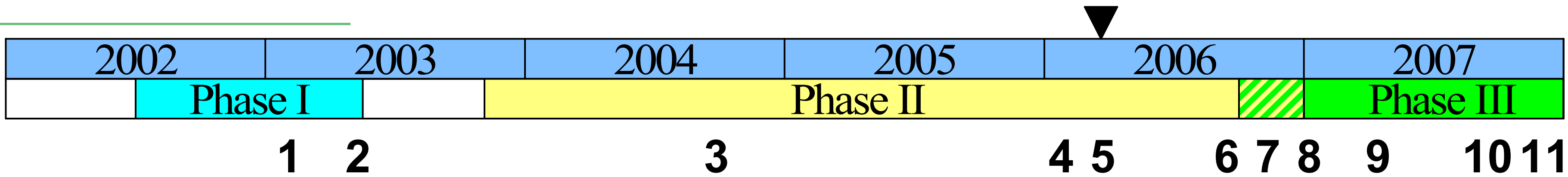

- **Phase I - Preliminary design**
  1. Preliminary component and system design
  2. Techno-economic study
- **Phase II - Detail design and optimization**
  3. Detail design and computer models
  4. Lab scale testing completed
  5. Full scale test apparatus constructed
  6. Proof of concept component testing completed
  7. Update system design and economic models
- **Phase III - Prototype system**
  8. Complete prototype design
  9. Build prototype system
  10. Verify system performance and update economics
  11. Commercialize system

Partners

- **Program partners**
  - Praxair, Inc.
    - Industrial gas technology leader
  - Boothroyd-Dewhurst, Inc.
    - Design For Manufacturing and Assembly (DFMA) experts
  - Diversified Manufacturing, Inc.
    - High temperature component fabrication experts
- **Additional experts**
  - Catalyst supplier
  - CFD modeling
  - High temperature materials

Budget - LCHPP Program

- Phase I
  - Completed 06/03
- **Phase II (10/03 - 06/06) - In progress**
  - Total estimated cost: $1,989,933
  - Cost share: 50/50 – $994,967 DOE/Praxair
  - FY2004 DOE funds (10/03 – 09/04) - $120,000 (actual)
  - FY2005 DOE funds (10/04 – 09/05) - $277,155 (actual)
  - FY2006 DOE funds (10/05 – 09/06) - $240,000 (actual)
  - DOE Phase II total shortfall in 2006 - $357,812 (projected)
- **Phase III (01/07 - 12/07)**
  - Total estimated cost: $3,856,000
  - Cost share: 50/50 – $1,928,000 DOE/Praxair
  - FY2006 DOE funds (10/05 – 09/06) - $0 (starts in 2007)

Phase II Plan and Program Structure

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- **1.0 Detail design**
  - 1.1 Hot component detail design
  - 1.2 Balance of plant detail design
  - 1.3 DFMA analysis
  - 1.4 Final detail design
  - 1.5 Tooling detail design
- **2.0 Computer modeling**
  - 2.1 Hot component assembly
  - 2.2 PSA system
  - 2.3 Auxiliary components
  - 2.4 System
  - 2.5 Update models based on test data
- **3.0 Component development and testing**
  - 3.1 Develop prototype test plan
  - 3.2 Design test facility
- ***3.0 Continued***
  - 3.3 Build test facility
  - 3.4 Startup/debug test facility
  - 3.5 Natural gas compressor
  - 3.6 Hot component testing
  - 3.7 System
- **4.0 Economics**
  - 4.1 Component cost study
  - 4.2 System economics
  - 4.3 Economies of scale
  - 4.4 Tooling cost analysis
  - 4.5 Market analysis
- **5.0 Phase III detailed plan**
- **6.0 Program management & reporting**

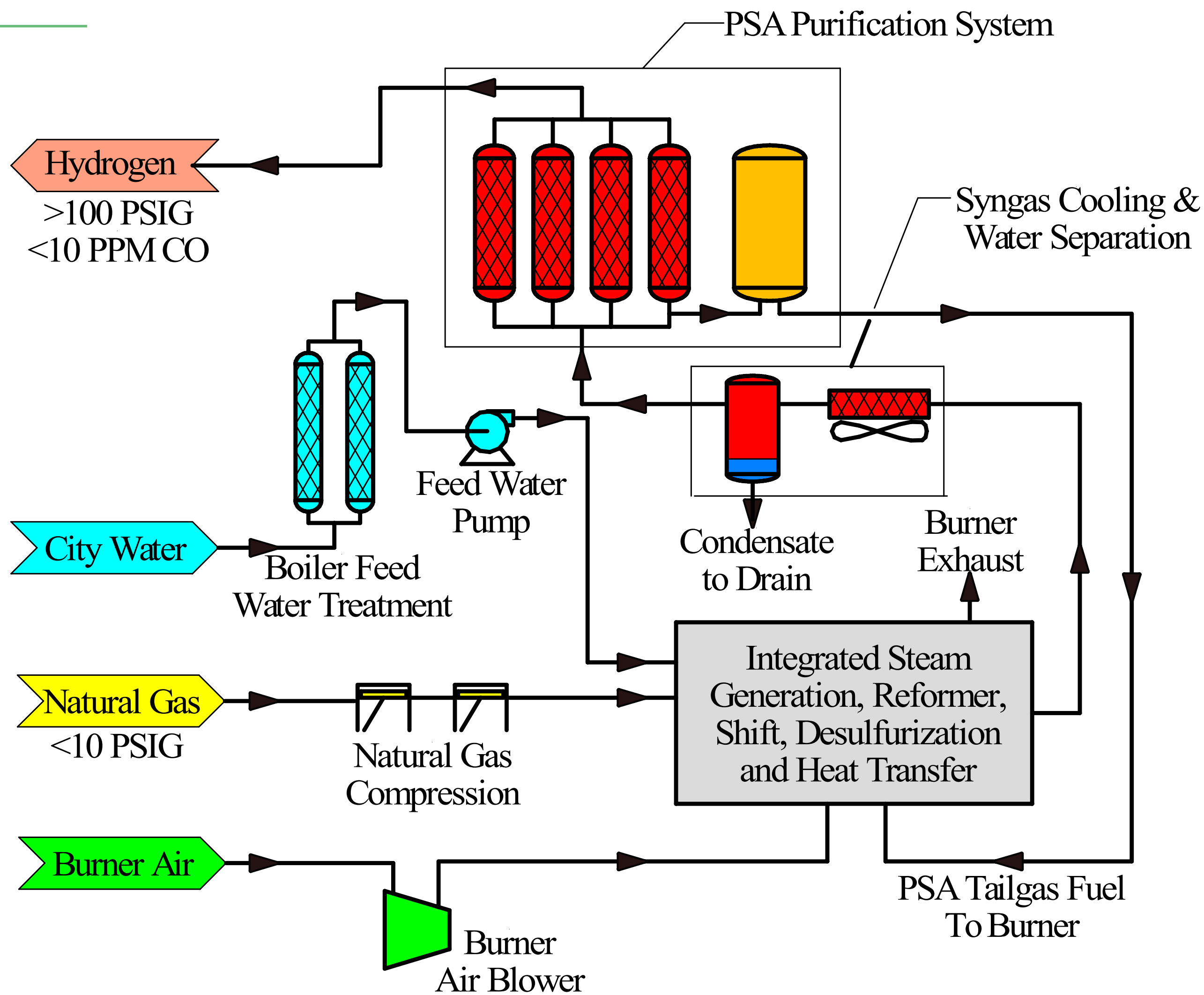
LCHPP

Design Specifications

- **Inputs**
  - Natural gas or equivalent
    - 5-30 PSIG
    - Std specifications
    - 850 SCFH
  - Water
    - Std potable specs
    - <0.5 GPM
  - Electrical
    - 220/480 VAC
    - 12 KW

- **Outputs**
  - Hydrogen product
    - 4.8 kg/h (2,000 scfh)
    - <10 PPM CO
    - >99% purity
    - 100-120 PSIG
  - Turndown capabilities
    - 50% minimum
  - System package
    - 7’-6” x 10’ x 10’
    - 18,000 lbs

LCHPP - Skid Process Flow



Overall System

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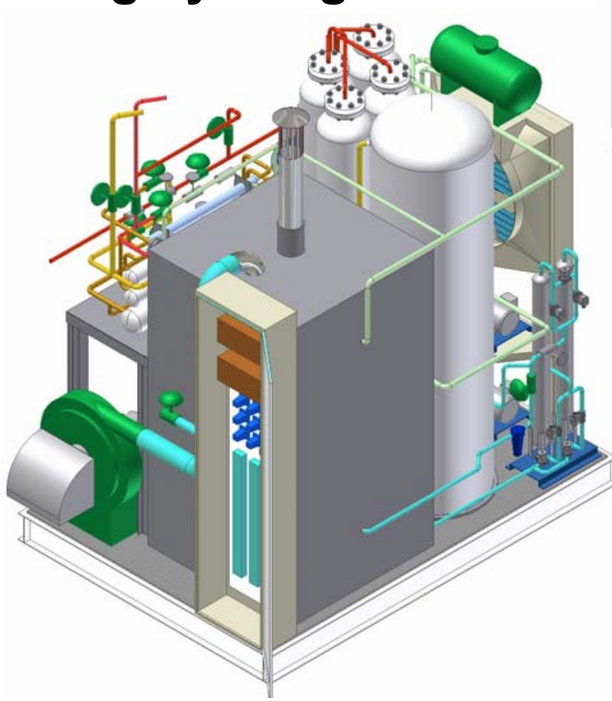
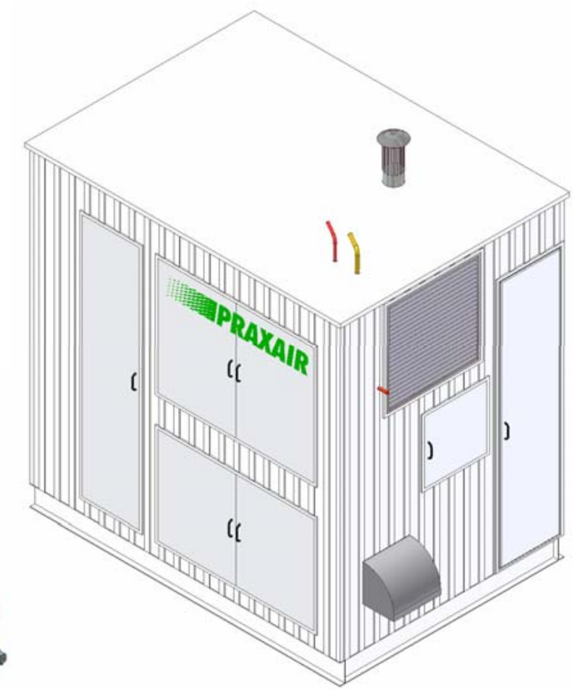
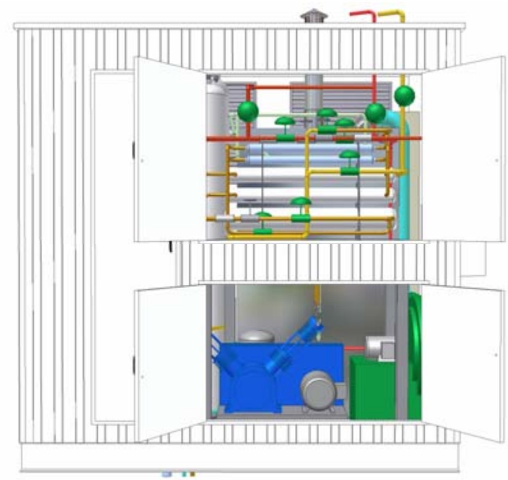
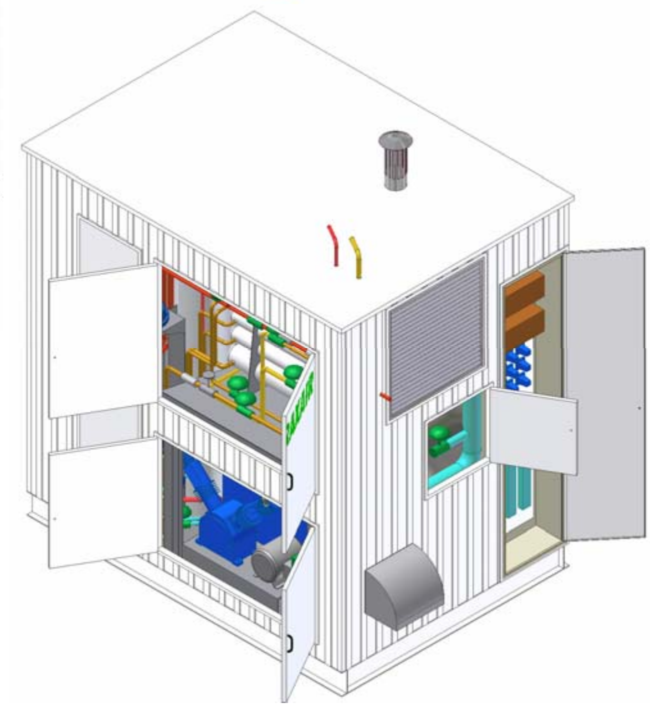
- Safety
- Compact, single skid
- Easily installed
- Welded construction
- Highly integrated









High Temperature Component

- **Functions**
  - Natural gas pre-heat
  - Desulfurization
  - Reforming
  - Water-gas shift reactor
  - Steam generation and superheat
  - Combustion
  - Air/exhaust/process heat exchange
  - Syngas cooling
- **Design**
  - DFMA
  - Highly integrated
  - Welded construction

LCHPP – Progress

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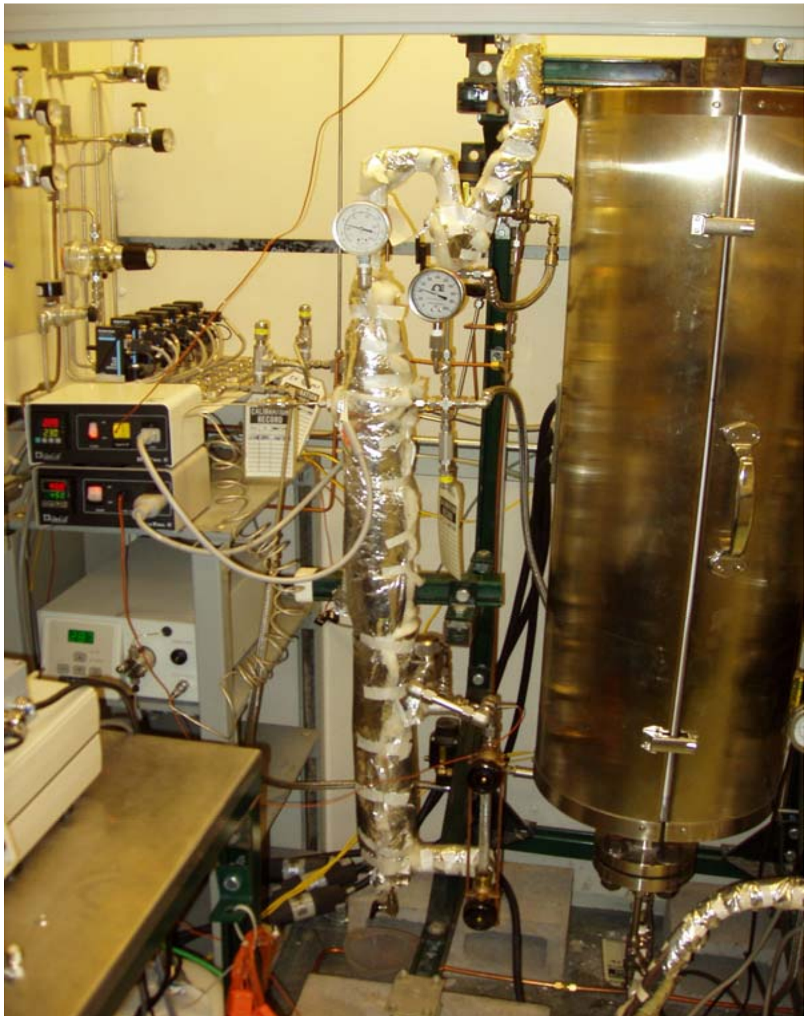
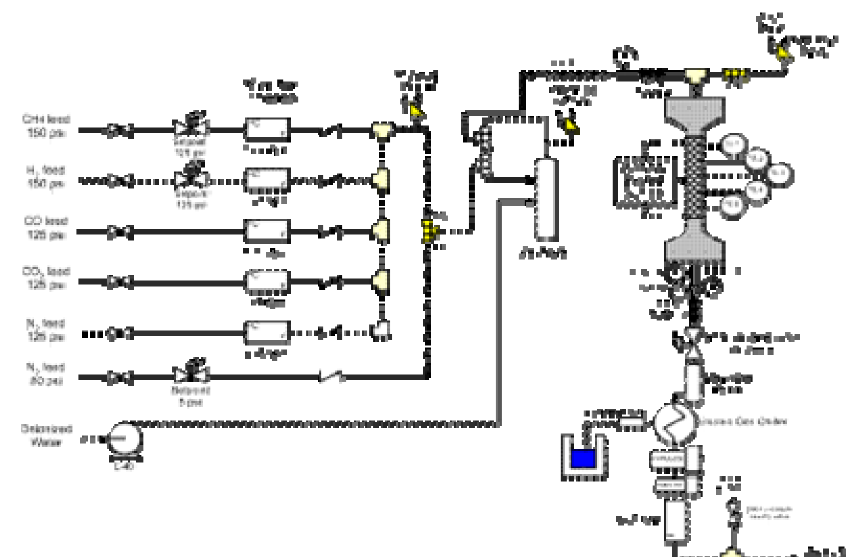
- **High temperature component**
  - Prototype design complete
  - Computer modeling complete
  - Material selection complete
  - Patent application submitted
- **Testing**
  - Lab scale reformer testing completed
  - Flow testing with full size mock-up of components completed
  - High temperature test rigs designed and fabricated
  - Testing underway
    - System configuration / thermal management
    - Catalyst
    - Burners
    - Auxiliary components

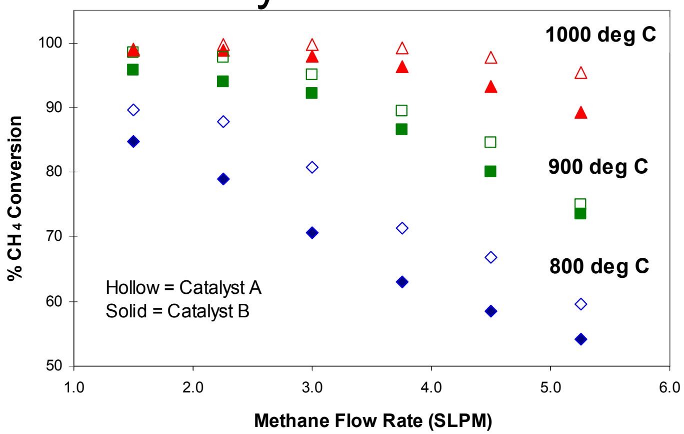
Lab Scale Testing



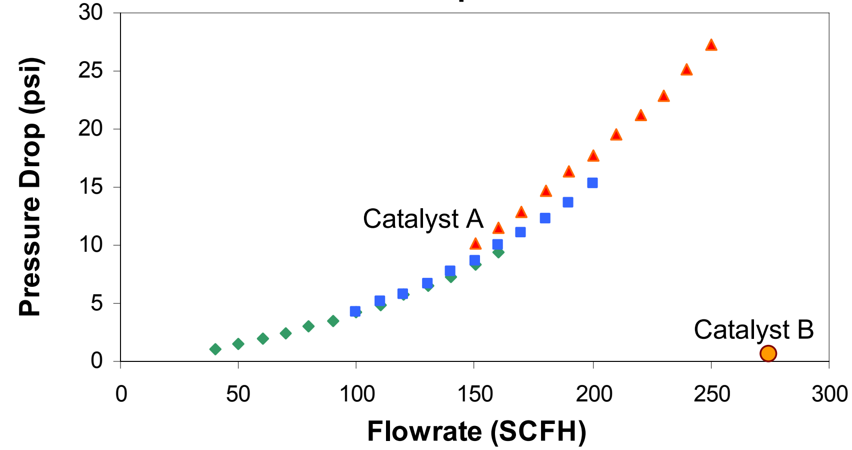


Lab Scale Testing - Results

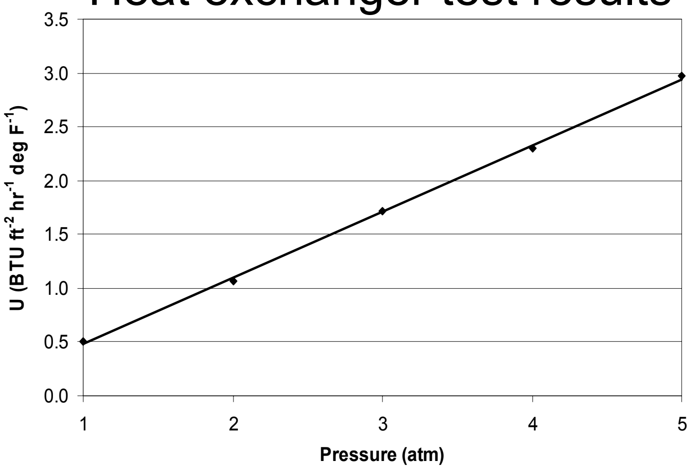
Catalyst test results



Pressure drop test results

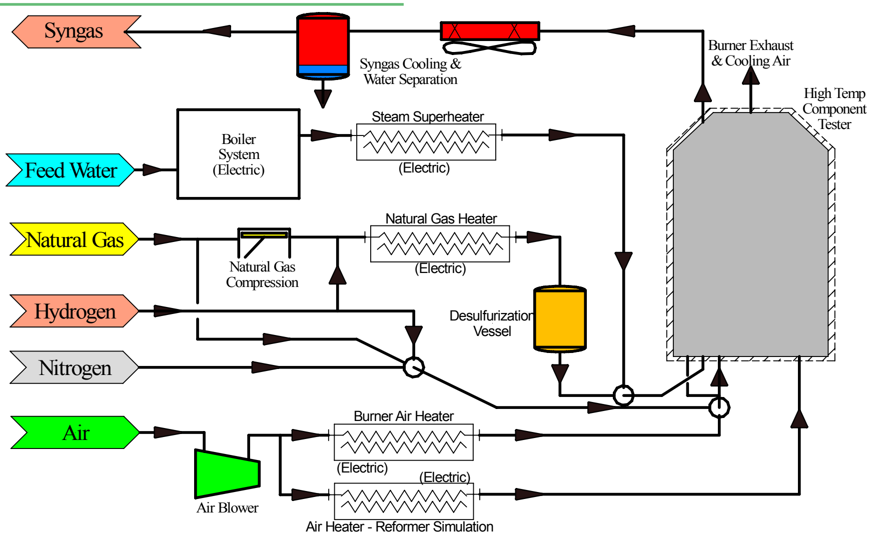


Heat exchanger test results



- **Testing results**
  - Catalyst configuration and pressure drop testing completed
  - Scaled reformer testing completed
  - Preferred catalyst chosen
  - Heat exchange analysis completed
    - Process models verified

Full Scale Test Rig



- **System**
  - Full scale burner
  - Air blower
  - Electric heaters (4)
  - Steam system
  - Natural gas, nitrogen and hydrogen gas supplies
  - GC gas analysis
  - Recording of 24 analog channels and 88 thermocouples
  - Testing
    - High temperature functions (reformer, shift reactor, heat transfer, steam generation)
    - Materials
    - Life testing

Accomplishments vs. DOE Barriers

- **A. Fuel processor capital costs**
  - Highly integrated system
  - “Off-the-shelf” components used wherever possible
  - No significant system cost increases from last year
    - Higher material costs
    - Part count reduced slightly
  - Unit capital cost comparable to plants 20x larger
  - Approaching overall DOE goals
  - Set new baseline for cost of H_2 from a small on-site system
- **B. Fuel processor manufacturing**
  - Extensive use of DFMA techniques (BDI)
    - Part count
    - Assembly time/complexity
  - Review of current design manufacturability (DMI)
  - Prototypes to verify results

Accomplishments vs. DOE Barriers - Continued

- **C. Operation and maintenance (O&M)**
  - Control system remote capability
  - Easy access to critical equipment
  - High quality components used
  - Designed for 15 year life (7.5 year high temp component life)
- **D. Feedstock and water issues**
  - Currently natural gas reforming
  - Considerations given to alternative feedstocks
  - Water treatment and steam system being tested
- **F. Control and safety**
  - Risk analysis completed
  - Full HAZOP review of system will be performed
  - All applicable standards will be followed
  - Develop safety and design standards (ISO TC197 working groups)

LCHPP - System Cost Model Parameters

- **Cost model assumptions**
  - Power - $0.08 $/kWh
  - Natural gas - $5.00 $/MMBtu, HHV
  - Water - $2.50 per 1,000 gallon
  - Capital recovery factor - 10% return, 20 year life
  - Catalyst life - 7.5 years (HT component refurbishment)
  - On-stream factor - 75%
  - Contingency - 10%
  - M&R - 3% of capital
  - Site labor
    - 15% @ 1 unit ===> 2% @ 1000 units

Technical Accomplishments / DOE Program Goals

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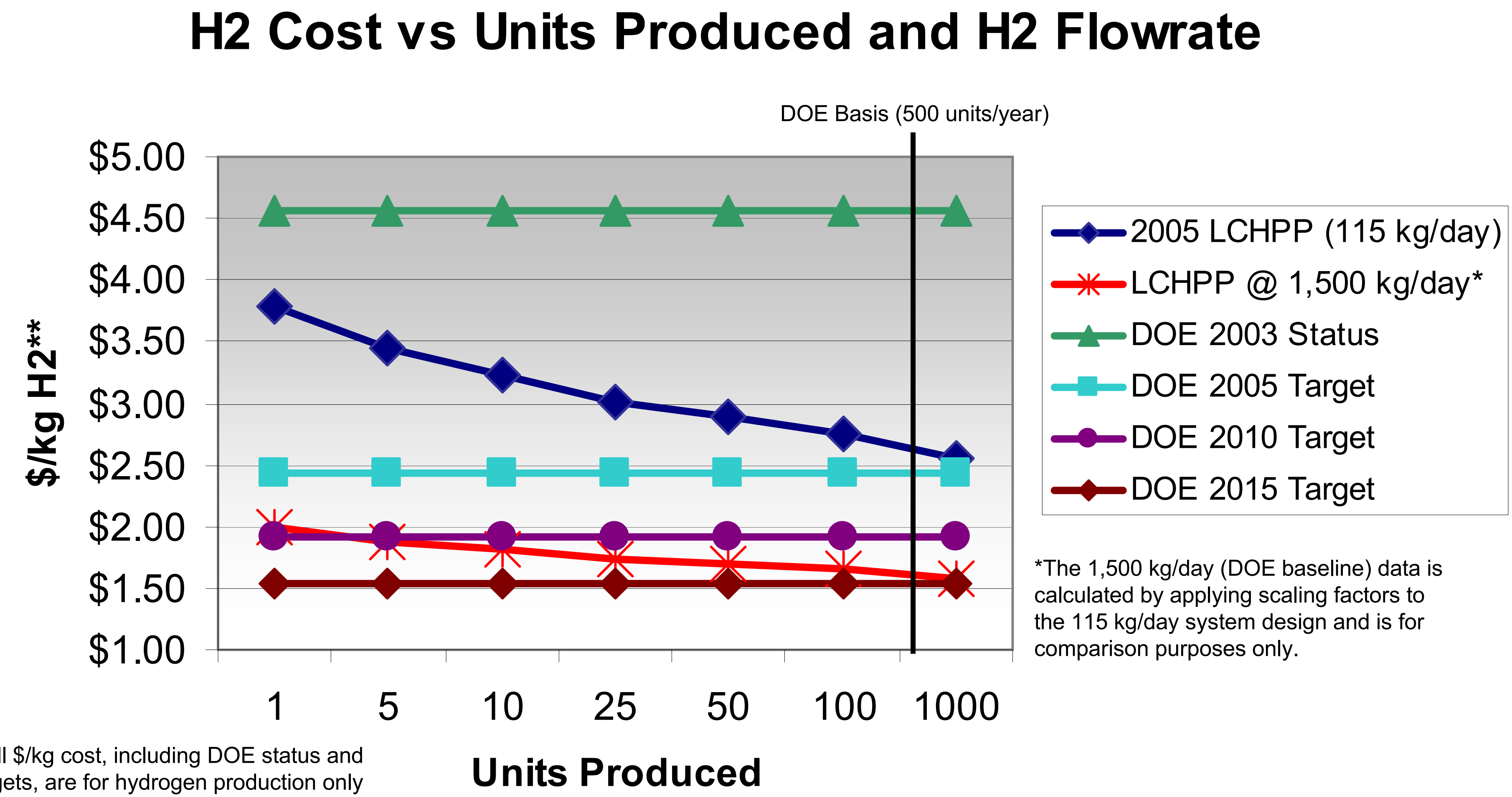

*The 1,500 kg/day (DOE baseline) data is calculated by applying scaling factors to the 115 kg/day system design and is for comparison purposes only.

**All $/kg cost, including DOE status and targets, are for hydrogen production only and exclude compression, storage and dispensing.

LCHPP - Future Work

- **Remainder of FY 2006**
  - Testing of components / proof of design
    - CFD modeling
    - Component testing
      - High temperature component - reformer, shift, desulfurization, heat transfer, burner, steam generation
      - High temperature materials
      - Natural gas compression
      - Pressure Swing Adsorption (PSA) system
      - Auxiliary components
    - Life testing
  - Comparative analysis with supply alternatives
  - Begin design of Phase III prototype system

LCHPP - Future Work

- **FY 2007 – Phase III of program**
  - Develop prototype system – components and skid
    - Design, fabrication and assembly
    - Testing
      - Possible integration into fueling station
      - Field experience
      - Life testing
  - Commercialize system
    - Economic models
    - Manufacturing plan
      - Production design, fabrication and assembly drawings
      - Design of jigs and fixtures
      - Supplier selection

LCHPP - Conclusions

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- **LCHPP program**
  - Low cost benchmark for small scale hydrogen production
    - Projected cost as low as $2.50/kg @ 4.8 kg/hr
  - Schedule extended per DOE request
    - Completion of Phase II at end of 2006
    - Completion of Phase III at end of 2007
  - Component testing underway
  - Full size prototype unit(s) available in 2007
    - Life testing of system
    - Placement at fueling station demo possible

Cooperative Efforts

- **Praxair**
  - Overall lead
- **Boothroyd-Dewhurst**
  - System optimization
  - Cost reduction / estimating
- **Diversified Manufacturing**
  - Manufacturing
  - Prototype development
- **Computer Modeling**
  - Reformer / shift design
  - Burner design
  - Heat transfer
- **Catalyst Supplier**

Low Cost Hydrogen Production Platform

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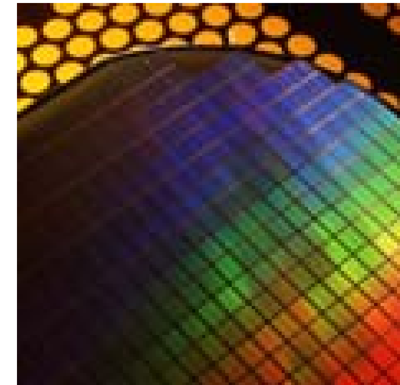

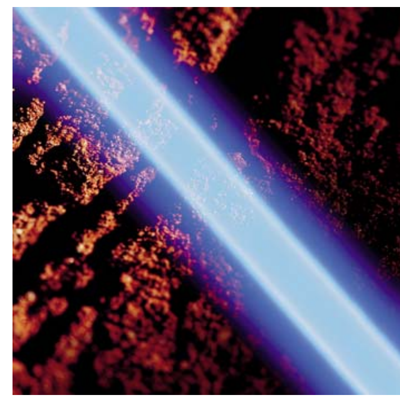

Questions?

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2005 Reviewers' Comments

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- **Is hydrogen compression and storage included in the project scope/economics?**
  - Compression, storage and dispensing are not included in the scope of this project. Other Praxair projects for both hydrogen fuel cell and industrial applications, including the Praxair LAX fueling station project, include this scope and are being monitored regarding integration potential into the LCHPP system.
- **Is 4.8 kg hydrogen per hour enough capacity for a typical refueling station?**
  - The summary of the analysis completed in Phase I of the program is as follows: An average gas station refuels 200 cars per day or supports 1,800 cars over a 9-day refilling cycle for a typical passenger car. A small plant producing 4.8 kg/h of hydrogen will be able to refuel 24 cars per day (or support 200 cars over the complete refueling cycle). For the average gas station, this range will represent 10% of the total automotive traffic. The assumption includes that the number of fuel cell vehicles will not likely exceed 10% of the total market share of vehicles through at least 2020.

LCHPP – Publications and Presentations

- **2006 International Forum on DFMA**
  - Paper and Presentation (Scheduled for June 2006)
    - DFMA Approach to Reducing the Cost of Hydrogen Produced from Natural Gas
- **ISO Technical Committee 197 - WG 9 (Member)**
    - ISO 16110-1 & 2: Hydrogen generators using fuel processing technologies
- **ISO Technical Committee 197 - WG 12 (Member)**
    - ISO 14687-2: Hydrogen Fuel – Product Specification – Part 2: PEM fuel cell applications for road vehicles

LCHPP – Critical Assumptions and Issues

- **Ease of maintenance issues**
  - Costs dictate integrated design (welded construction)
  - Risk mitigation
    - Verification of design with comprehensive testing
    - Ability to access and replace key components
    - High temp comp designed for 7.5 year life, field removal and shop refurbishment
- **Still a miniature chemical plant**
  - LCHPP has all the unit operations of a big SMR plant
  - Goal to compete with 20X larger systems
  - Risk mitigation
    - DFMA to reduce part count and complexity
    - Continued analysis of competing technologies
- **Public acceptance**
  - Plants likely to be more accessible to public (gas station)
  - Local building and fire inspectors could delay/stop projects
  - Risk Mitigation
    - Comply with all existing safety and design standards
    - Develop new standards as required
    - Offer training and informational materials to public and local officials
    - As more hydrogen systems are online, public acceptance should increase