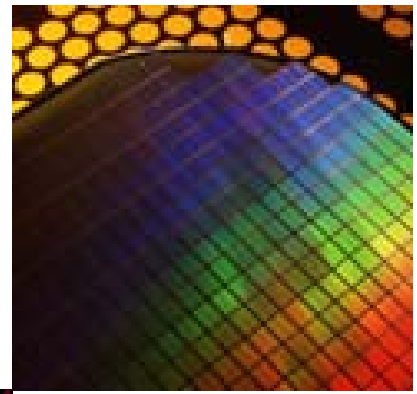
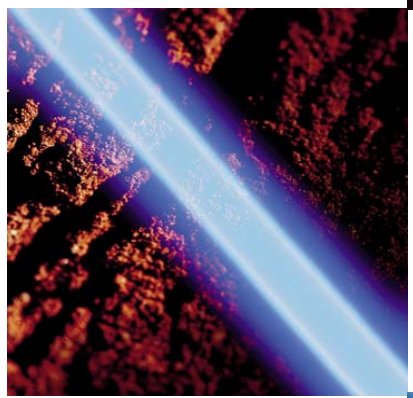
Low Cost Hydrogen Production Platform

Cooperative Agreement: DE-FC36-01GO11004
Project ID #: PD1





Timothy M. Aaron

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

DOE Hydrogen Annual Review Meeting
May 15 - 18, 2007

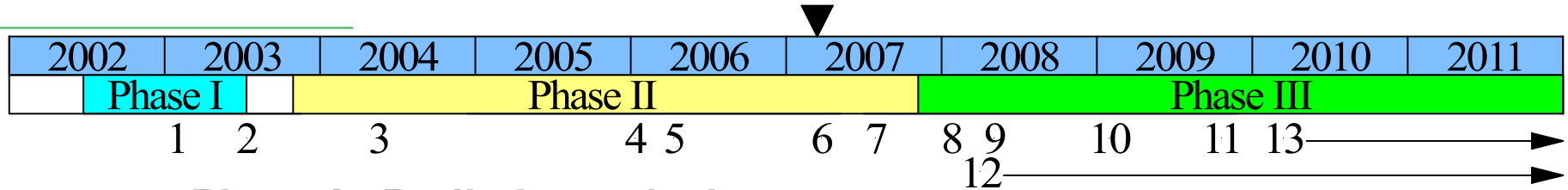
DOE Hydrogen Program

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

LCHPP – Objectives

- **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 (production only)
  - Gas station capacity and size - Single, easily installed skid
- **Fueling station integration**
  - Prototype construction
  - LAX fueling station
    - Installation and operation (2 years)
    - High pressure (700 bar) compression and dispensing
- **DOE barriers addressed (top 3) – Hydrogen Production**
  - A. Reformer capital costs
  - B. Reformer manufacturing
  - C. Operation and maintenance (O&M)
- **DOE barriers addressed (top 3) – Technology Validation**
  - C. Lack of hydrogen refueling infrastructure performance and availability data
  - D. Maintenance and training facilities
  - E. Codes and standards

DOE Project Timeline



- **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 & fueling station integration**
  8. Complete prototype design
  9. Build prototype system
  10. Verify system performance and update economics
  11. Commercialize hydrogen system
  12. Hydrogen compression to 700 bar (10,000 psig) (LAX)
  13. Fueling station integration (LAX)

Budget - LCHPP Program

- **Phase I**
  - Completed 06/03
- **Phase II (10/03 - 06/06) - In progress**
  - Total budgeted 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) - $300,000 (actual)
  - FY2007 DOE funds (10/06 – 09/07) - $ 15,000 (to date)
  - DOE Phase II total DOE shortfall to date - $285,812
- **Phase III (10/07 - 12/11) - Technology Validation**
  - Cost share: 50/50
  - FY2007 DOE funds (10/06 – 09/07) - $0

Approach

- **Phase II – Hydrogen Production**
  - Complete component testing
  - Prove system design
  - Procure prototype long lead materials
  - Update prototype design
  - Final report and Phase III proposal
- **Phase III – Prototype System**
  - HAZOP and safety reviews
  - Construction
  - Installation
  - Control system
  - Performance testing
  - System economics
  - Economies of scale
  - Tooling cost analysis
  - Market analysis
- **Phase III – 700 bar compression (LAX)**
  - Analysis of options
    - Compression
    - Dispensing
    - Integration
  - Project scope / definition
  - HAZOP and safety reviews
  - Site characterization & permitting
  - Procurement
  - Installation
  - Operation and support
- **Phase III – Prototype (LAX)**
  - Project scope / definition
  - Site characterization & permitting
  - Installation
  - Operation and support

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

System

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

PRAXAIR

High Temperature Component

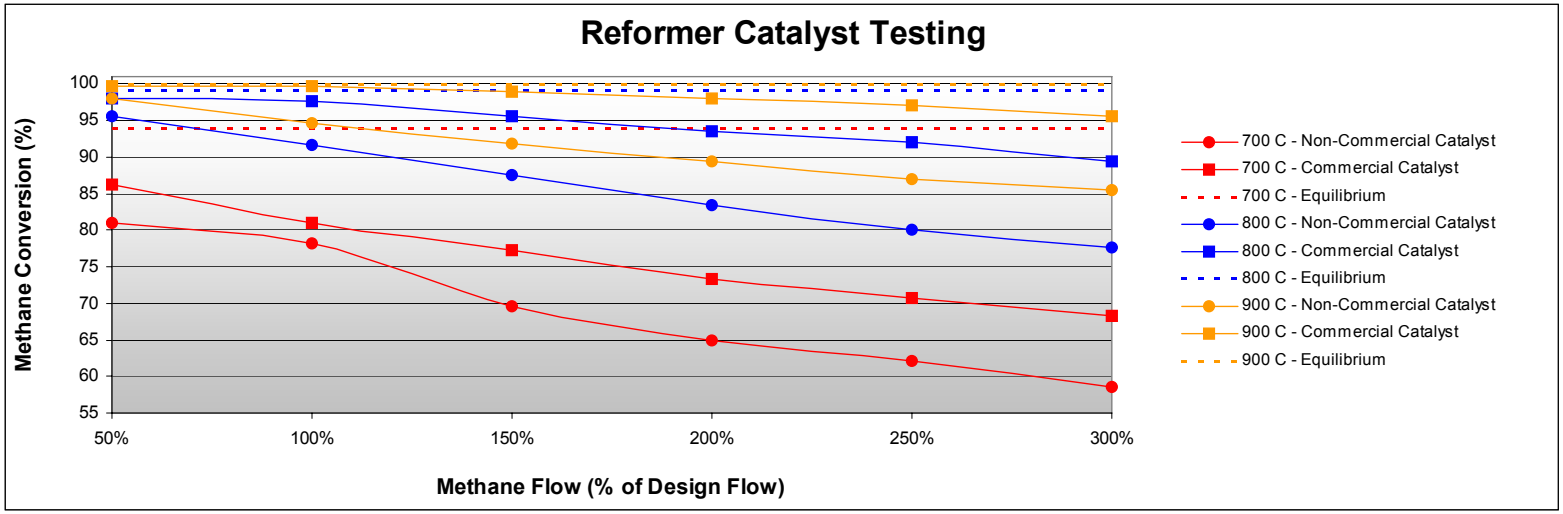
- **Functions**
  - Natural gas pre-heat
  - Desulfurization
  - Reforming
  - Water-gas shift reactor
  - Steam generation and superheat
  - Combustion
  - Air/exhaust/process heat exchange
  - Syngas cooling
- **Design**
  - DFMA
  - Highly integrated
  - Welded construction

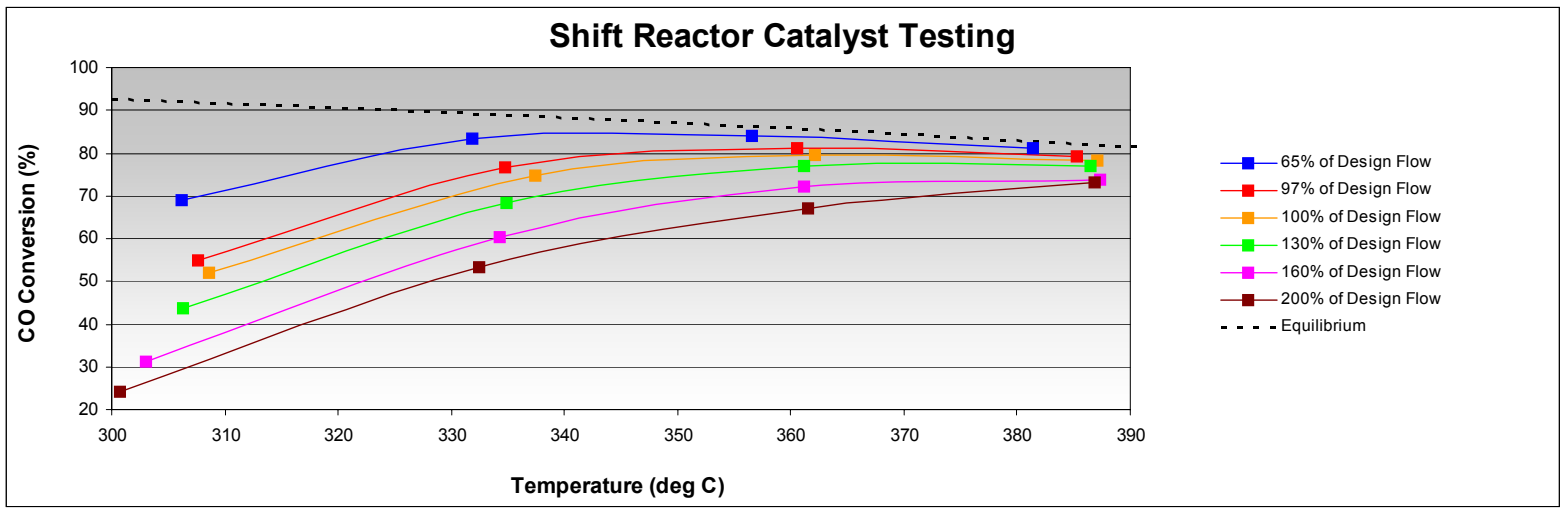
LCHPP – Accomplishments

- **High temperature component**
  - Prototype design complete
  - Computer modeling complete
  - Material selection complete
  - Patent application submitted
- **Testing**
  - Lab scale reformer testing completed
  - Full scale testing continues
    - Reformer thermal management proven
      - Optimization testing underway
    - Catalyst
    - Burners
    - Steam system
    - Auxiliary components

Catalyst courtesy of Johnson-Matthey

LCHPP – Accomplishments (Catalyst Testing)





Accomplishments vs. DOE Barriers

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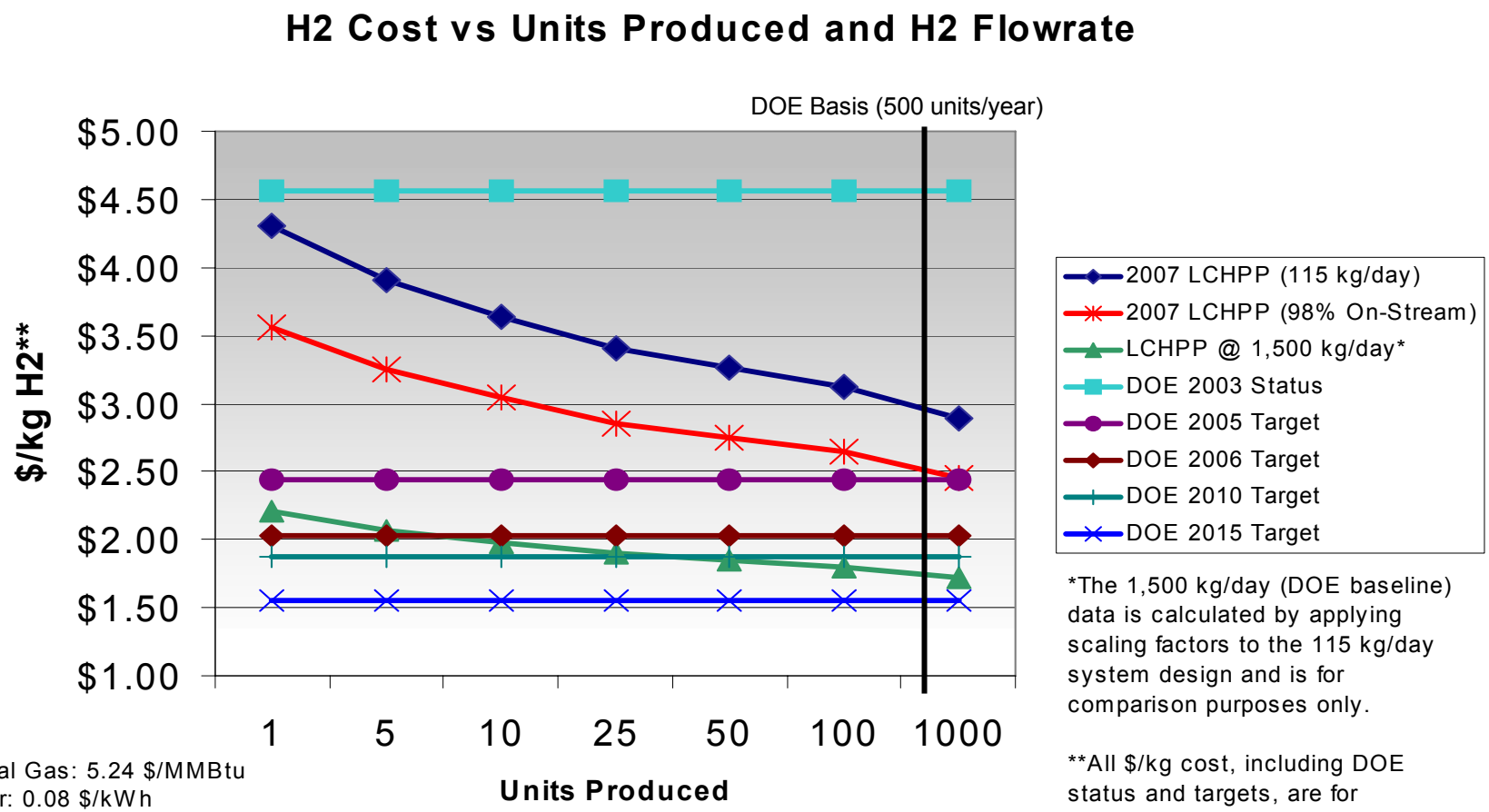
- **A. Fuel processor capital costs**
  - Highly integrated system
  - “Off-the-shelf” components used wherever possible
  - No significant system cost increases from last year
    - Higher material costs
    - Part count nearly identical
  - Unit capital cost comparable to plants 20x larger
  - Approaching overall DOE goals
  - Set new baseline for cost of H2 from a small on-site system
- **B. Fuel processor manufacturing**
  - Extensive use of DFMA techniques (BDI)
    - Part count
    - Assembly time/complexity
    - Welded construction
  - 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 refurbishment)
- **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)

Technical Accomplishments / DOE Program Goals

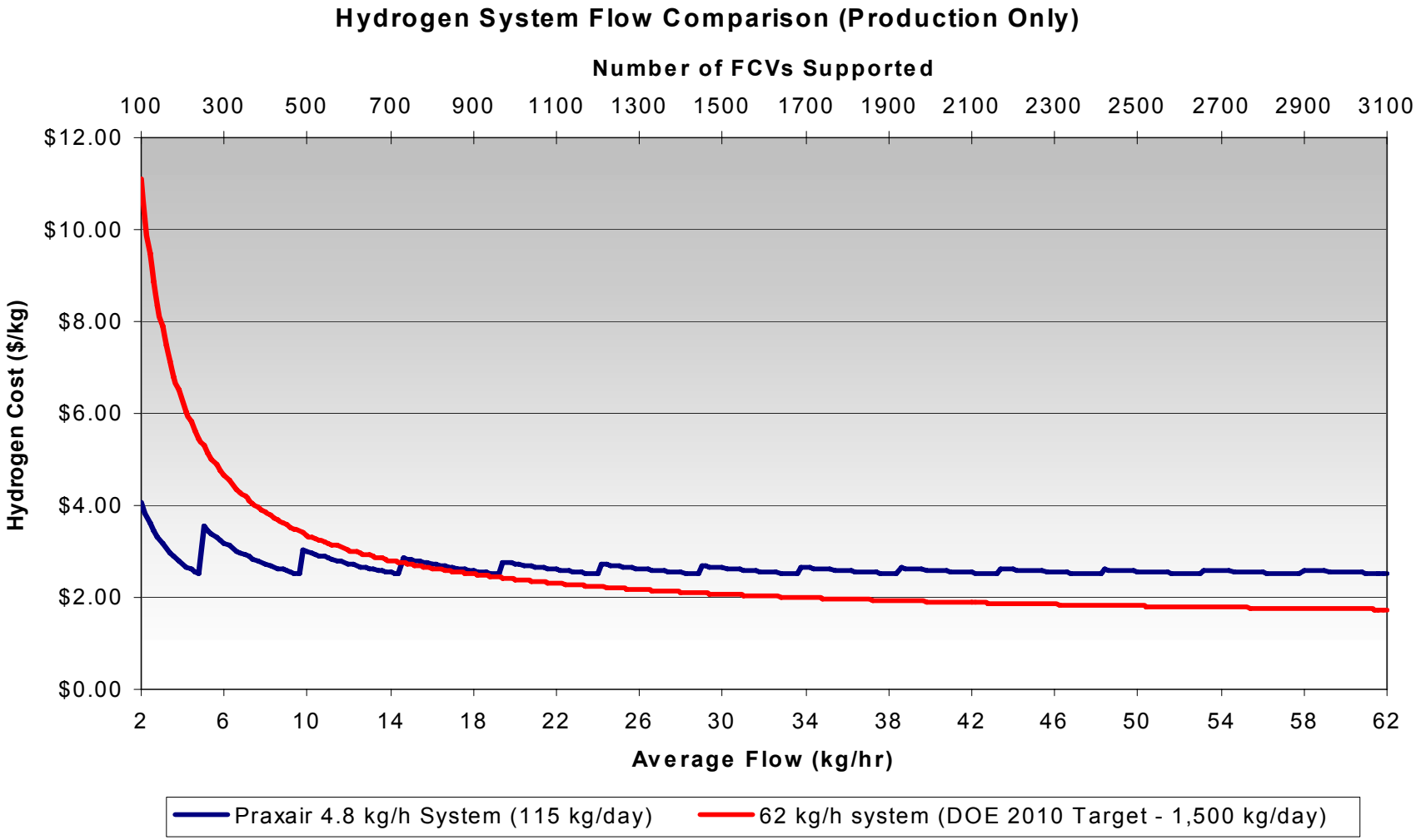


Natural Gas: 5.24 $/MMBtu
Power: 0.08 $/kWh
On-Stream Factor: 70%
Contract Life: 20 years
M&R (% of Cap per Year): 3%

*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.

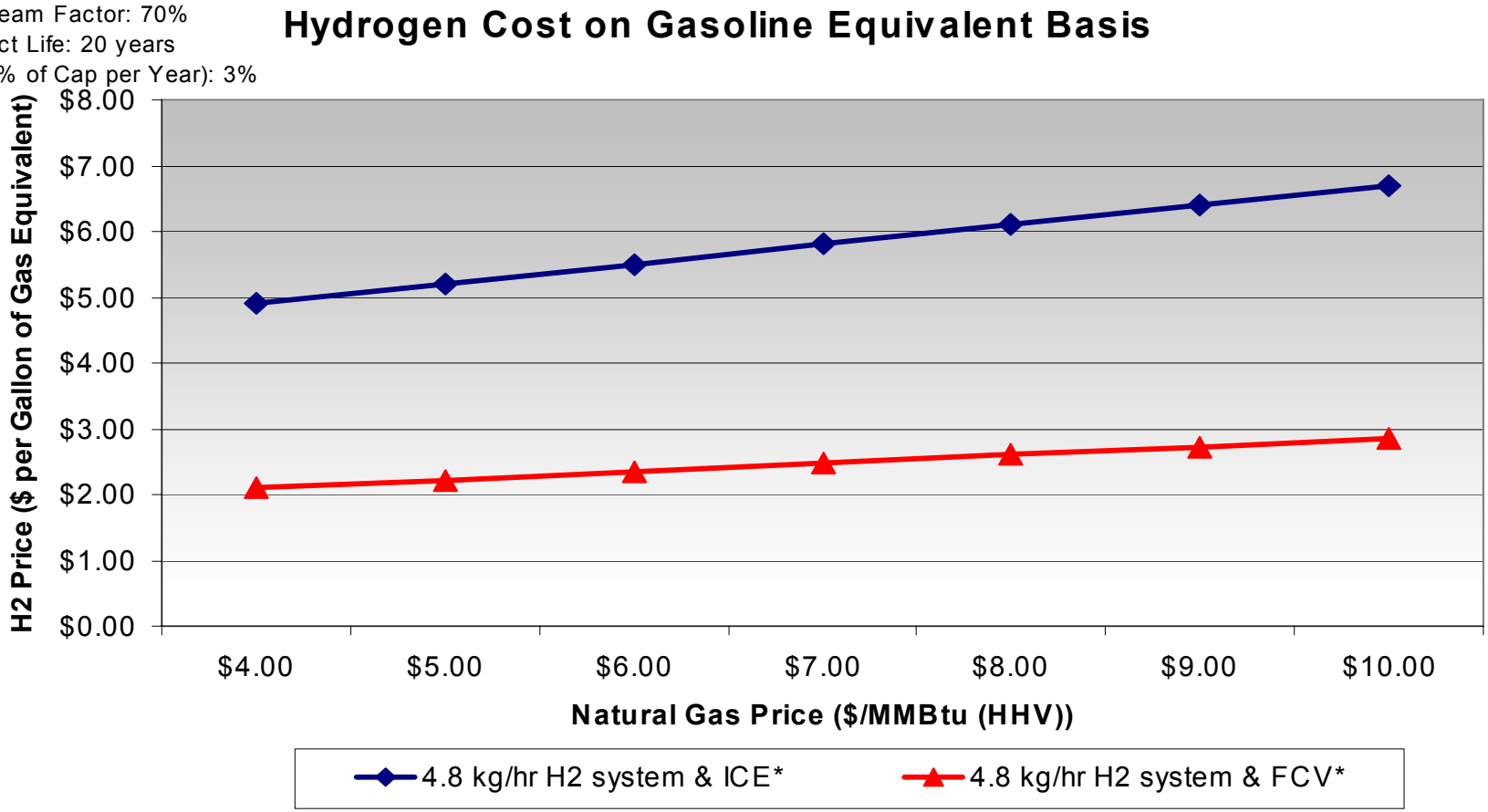
**All $/kg cost, including DOE status and targets, are for hydrogen production only and exclude compression, storage and dispensing.

Fueling Station H2 Cost Analysis



Hydrogen Cost vs. Gasoline

Power: 0.08 $/kWh
On-Stream Factor: 70%
Contract Life: 20 years
M&R (% of Cap per Year): 3%



*Assumes that the cost of H2 storage and fuel cell capital are similar to the current hybrid ICE vehicles. Cost includes compression and dispensing

ICE Hybrid Baseline (MPG gasoline): 43
FCV MPG Equivalent (GGE MPG hydrogen): 75
H2 ICE MPG Equivalent (GGE MPG hydrogen): 32
Percent total cost increase for comp & dispensing: 30%

LCHPP - Future Work

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- **Remainder of FY 2007**
  - Testing of components / proof of design
    - Complete the 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
  - Complete the design of prototype
  - Procurement of prototype long-lead materials

LCHPP - Future Work

- **FY 2008 – Phase III of program**
  - Develop prototype system – components and skid
    - Fabrication and assembly
    - Testing
    - 700 bar hydrogen compression at LAX
- **FY2009-11 – Phase III**
  - Prototype at LAX fueling station
    - Installation and integration
    - Field experience
  - Commercialize system
    - Economic models
    - Manufacturing plan
      - Production design, fabrication and assembly drawings
      - Design of jigs and fixtures
      - Supplier selection

LCHPP - Summary

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- **LCHPP program**
  - Low cost benchmark for small scale hydrogen production
    - Projected cost as low as $2.75/kg @ 4.8 kg/hr
  - Revised schedule
    - Completion of Phase II at end of 2007
    - Completion of Phase III at end of 2011
  - Component testing nearing completion
  - Prototype procurement underway
  - Full size prototype unit available in 2008
    - Life testing of system
  - Placement at LAX fueling station
    - 2008 - 700 bar hydrogen compression and dispensing
    - 2009 – Hydrogen system

Cooperative Efforts

- **US Department of Energy**
  - Sponsor
- **Praxair**
  - Overall lead
- **Boothroyd-Dewhurst**
  - System optimization
  - Cost reduction / estimating
- **Diversified Manufacturing**
  - Manufacturing
  - Prototype development

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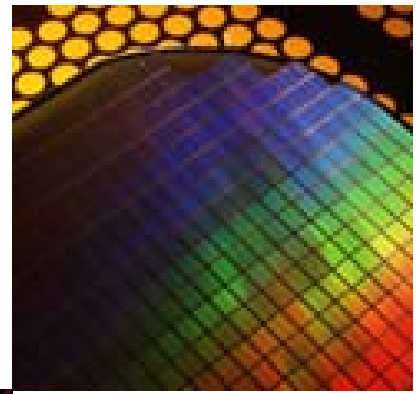

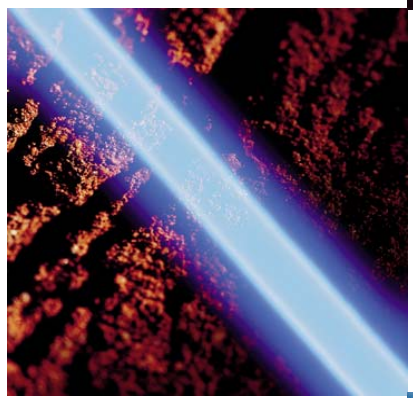

Questions?

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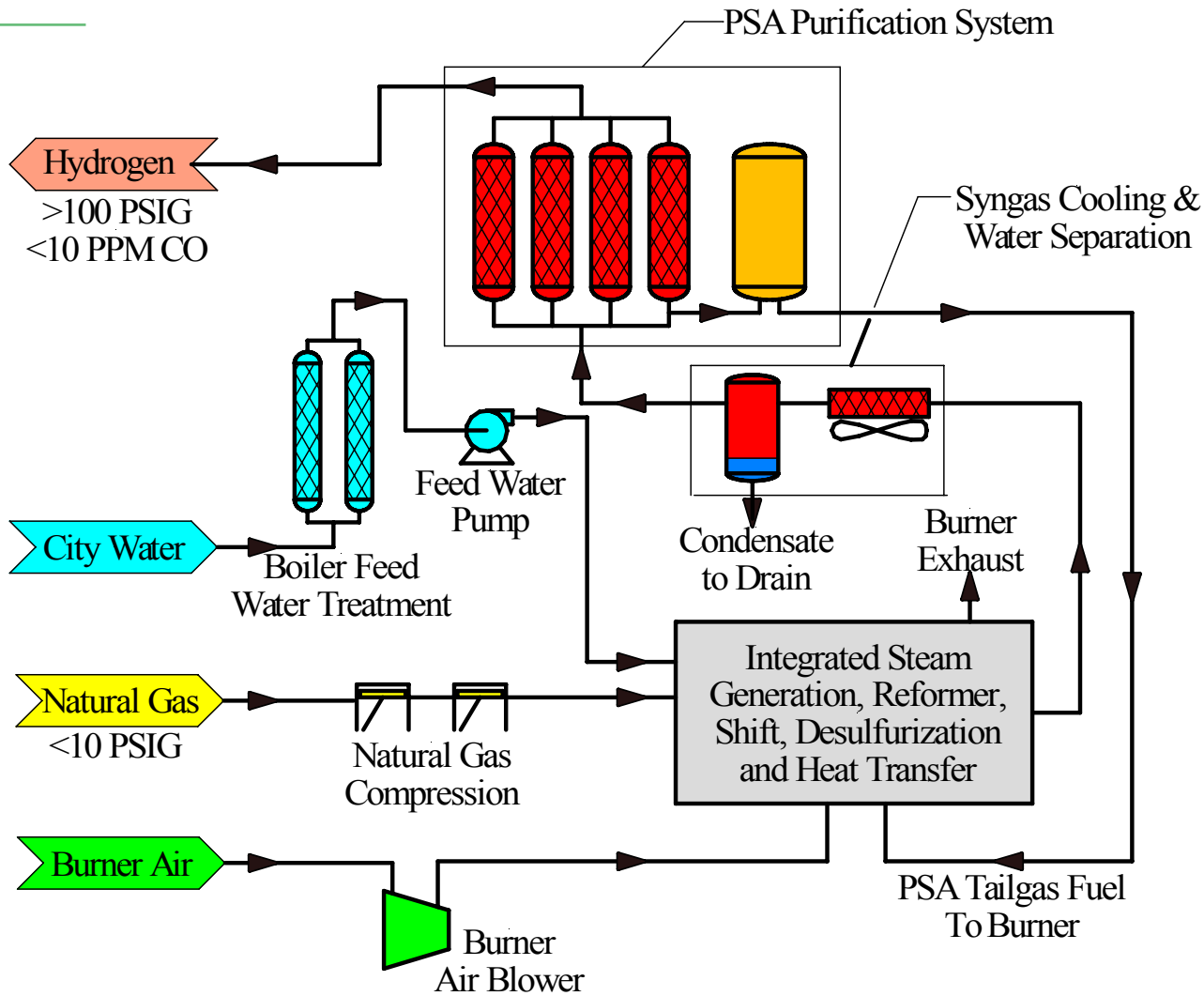
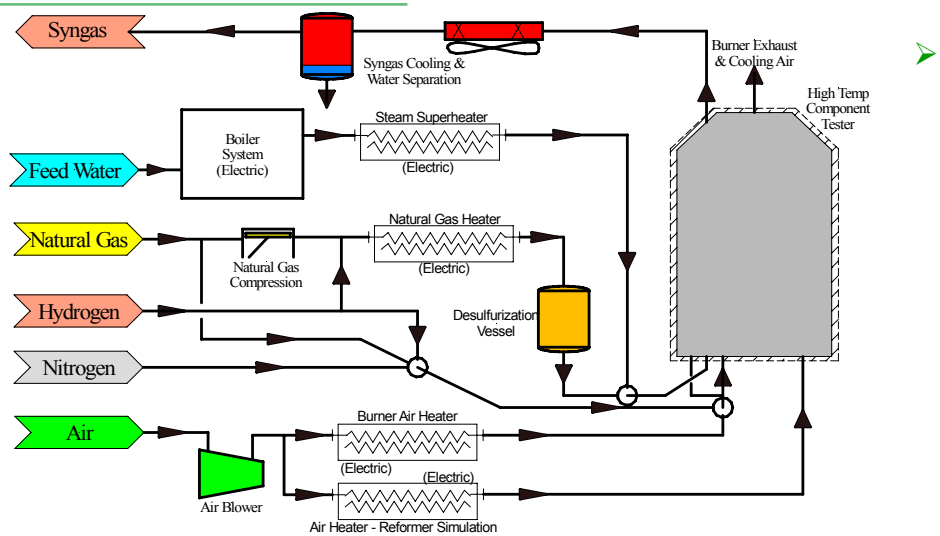
Praxair Hydrogen

- **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 - Skid Process Flow



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