

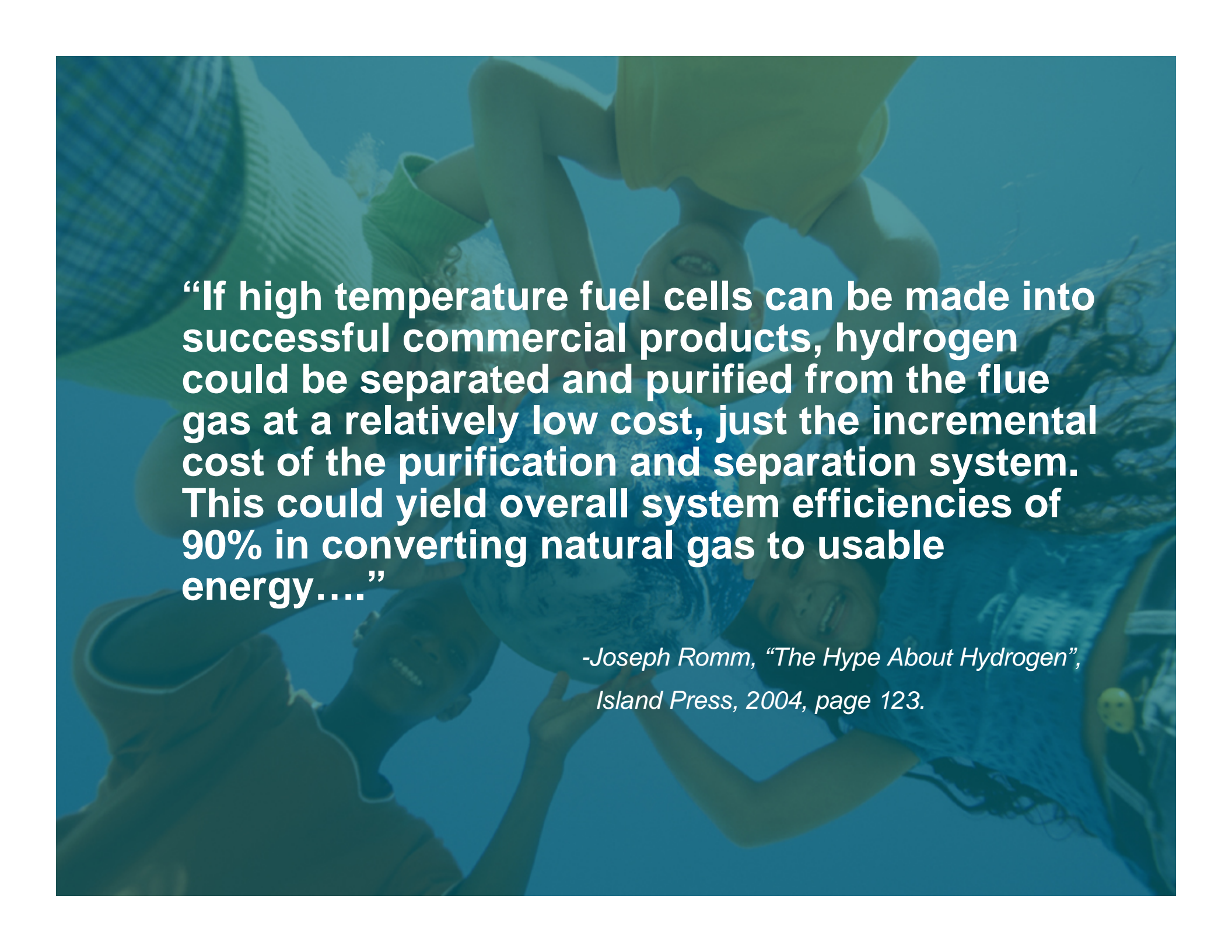
Validation of An Integrated System for a Hydrogen-Fueled Power Park

Project ID # TV5

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U.S. D.O.E. – Hydrogen Program Annual Review
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This presentation does not contain any proprietary or confidential information.

A group of diverse children are shown from the chest up, holding a globe of the Earth. They are all smiling and looking towards the camera. The background is a soft, out-of-focus blue. The text is overlaid on the image in a white, sans-serif font.

“If high temperature fuel cells can be made into successful commercial products, hydrogen could be separated and purified from the flue gas at a relatively low cost, just the incremental cost of the purification and separation system. This could yield overall system efficiencies of 90% in converting natural gas to usable energy....”

*-Joseph Romm, “The Hype About Hydrogen”,
Island Press, 2004, page 123.*

Objectives

● Overall Project

- To demonstrate the economic and technical viability of a hydrogen energy station using a high temperature fuel cell designed to produce power and hydrogen
- Maintain safety as a top priority in the system design and operation

● Past Year

- Complete preliminary feasibility analysis
- Phase 2 Go / No-Go Decision
- Initiate Phase 2 Design Effort
 - Select Fuel Cell Technology
 - Begin Design and Engineering Development Effort

Objectives by Phase

- ✓ ● **Phase 1A- Evaluated PEM (Completed FY03)**
- ✓ ● **Phase 1B- Evaluation of HTFC Coproduction (Completed FY04)**
 - Co-production efficiencies: 55%-60% (LHV)
 - Potential to meet the DOE targets while producing power for less than 0.10 \$/kW
- **Phase 2- System Design In Progress (In Progress)**
 - ✓ – Select HTFC Technology
 - Engineering Development
 - Preliminary Design
 - Cost Estimate
 - Update Technical & Economic Assumptions
 - Site Selection
 - GO / No-GO Decision
- **Phase 3: Detailed Design and Construction (FY05 – 06)**
- **Phase 4: Operation, Testing, Data Collection (FY06 – 07)**

Overview: Budget

- Total Project Budget:
 - \$1.391 MM
- Cost Sharing:
 - DOE - \$0.695 MM
 - APCI and Partners – balance.
- FY2004 Total Spend
 - \$100 k
- FY2005 DOE Funding
 - \$ 573 k Estimated

Overview: Technical Barriers and Targets

- DOE Technical Barriers

- Technical Validation (Section 3.5.4 of HFCIT Program Report), Task #4.
 - B. Storage
 - C. H₂ Refueling Infrastructure
 - I. Hydrogen and Electricity Coproduction

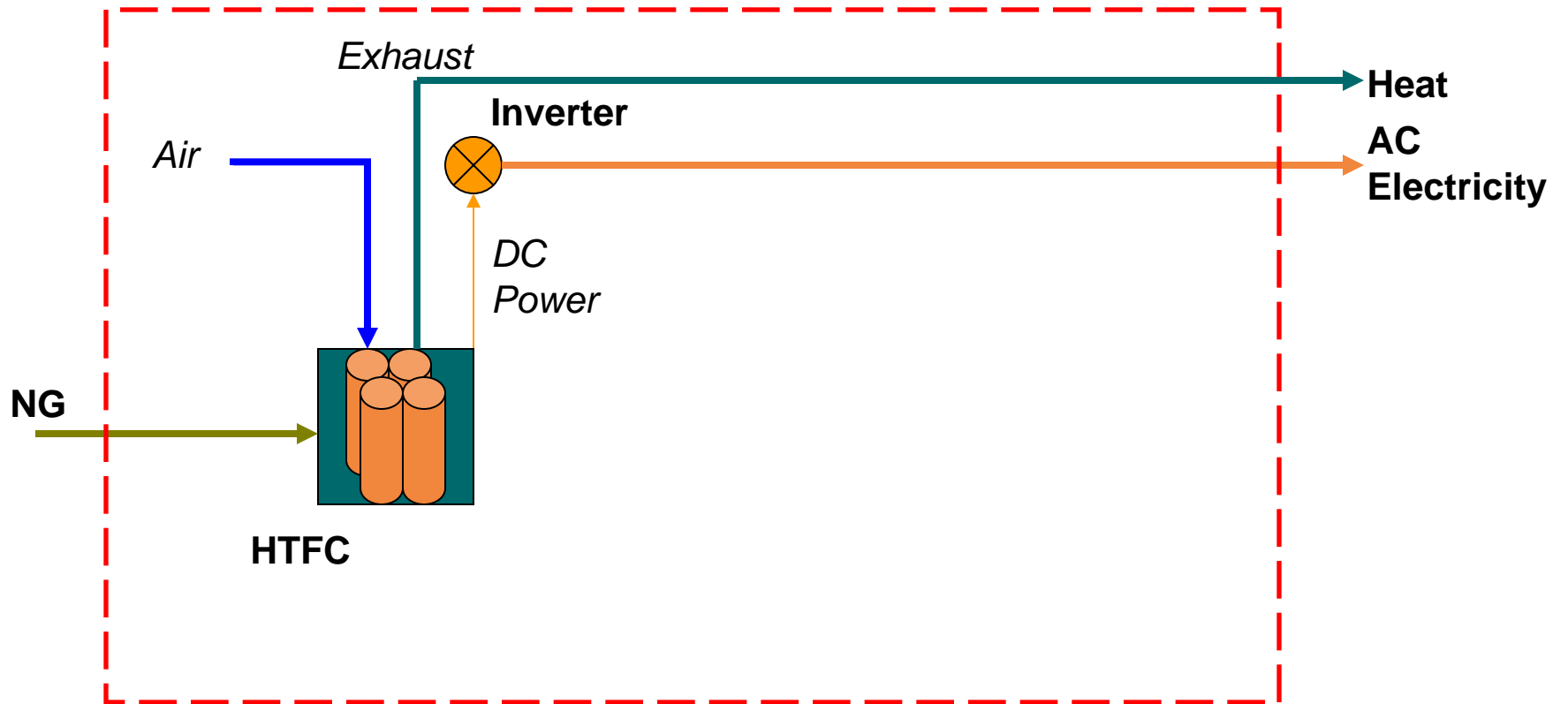
- DOE Targets

- H₂ Production (Table 3.1.2 of HFCIT Program Report), Task #3.
 - Cost of H₂:
 - \$3/kg 2005
 - \$1.50/kg 2010
- Energy Station Coproduction of H₂ and Electricity (Table 3.1.2, Task #4)
 - Durability >40,000 hours
 - Electrical Efficiency >40%

Approach

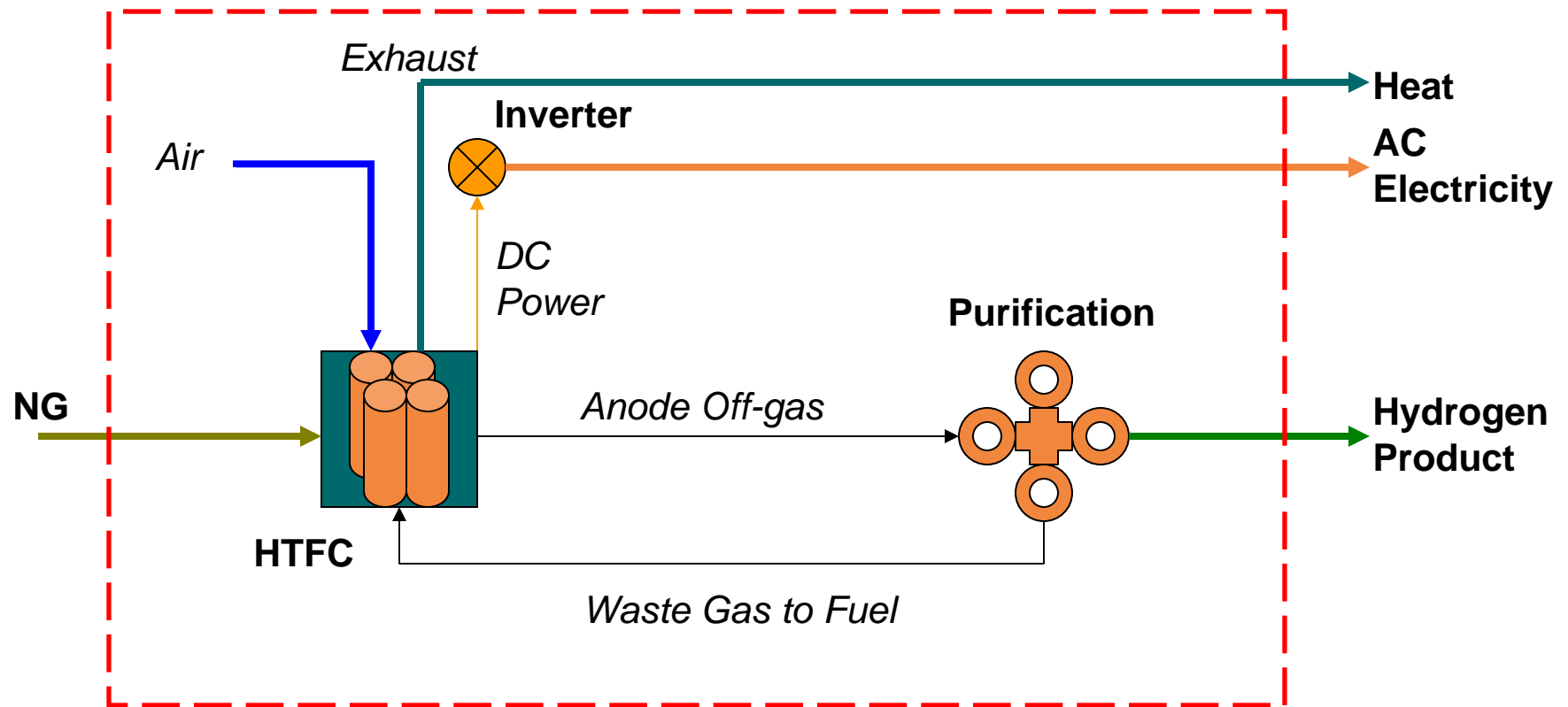
- **Design and demonstrate a hydrogen energy station using a high temperature fuel cell (HTFC) designed to produce electricity and hydrogen**
 - **Background**
 - **Benefits of HTFC**
 - **Economic Case for HTFC**
 - **Industrial**
 - **Hydrogen Economy**

High Temperature Fuel Cell (HTFC)



Electrical Efficiency (LHV): 45 – 55 %

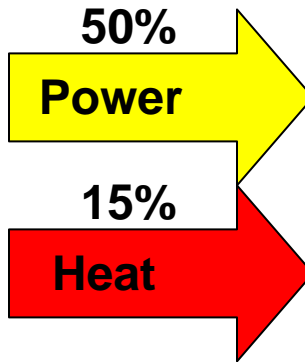
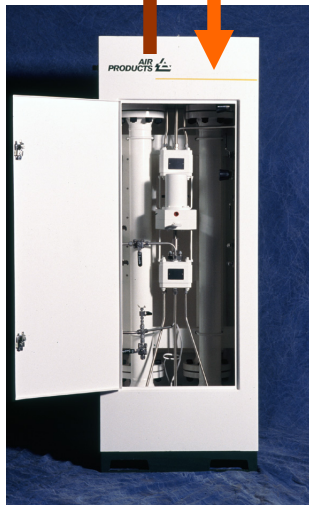
High Temperature Fuel Cell (HTFC) with Hydrogen Coproduction



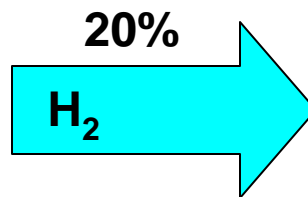
Potential Co-Production Efficiency (LHV): 55 - 60%

Distributed Power and Hydrogen

FuelCell Energy DFC-300



The Plaza at PPL Center, Allentown



Benefits of HTFC Coproduction

- High efficiency
- Low emissions
- Utility Bundling (power, hydrogen, & heat)
 - Economies of Scale and Scope
 - Operation and Maintenance Synergy
 - Improves capital utilization
 - More flexible pricing options- 2 or 3 Levers
- Fuel cell / fuel cell hybrid option
 - Efficient Cycle
 - No turbine- potential for higher reliability and less maintenance
- Improved Fuel Cell Economics

Economic Benefit- Industrial Example

| | Units | Heat & Power | Heat, Power & Hydrogen |
|-----------------------------|-----------------|--------------|------------------------|
| Purchased Power Cost | \$/kWh | 0.07 | 0.07 |
| Natural Gas Cost | \$/mmbtu | 6.00 | 6.00 |
| Steam Cost | \$/mmbtu | 7.50 | 7.50 |
| Hydrogen Cost | \$/kg | | 4.25 |
| | | | |
| Installed Cost | \$/kW | 2000 | 3000 |
| | | | |
| Payback | years | 8.65 | 4.21 |

Hydrogen product improves economics for high temperature fuel cells

Economic Benefit- Fueling Example

| | 2005 | 2010 | 2015 |
|----------------------------------|---------|---------|----------|
| Hydrogen, kg/day* | 690 | 690 | 690 |
| Net Electricity, kw | >1.5 MW | >1.5 MW | > 1.5 MW |
| HTFC Cost, \$/kW AC w/o H2 | 2250 | 1200 | 800 |
| Natural Gas Costs, \$/mmbtu* | 4.00 | 4.00 | 4.00 |
| Production Volume, units/year* | 100 | 100 | 100 |
| Fueling Utilization* | 90% | 90% | 90% |
| Capital Factor* | 0.11 | 0.11 | 0.11 |
| Fueling Scenario | | | |
| Hydrogen Production Price, \$/kg | 2.52 | 1.15 | 1.15 |
| Power Price, \$/kwh | 0.08 | 0.07 | 0.06 |

*Assumptions from the DOE Multi-Year Research, Development and Demonstration Plan, Table 3.1.2, page 3- 10, Draft 6/3/03.

Program Progress

- **Completed Phase 1 Feasibility Analysis**
- **Proceeding with Phase 2- Engineering Design and Development Program**
 - Fuel Cell Technology Selected
 - Engineering Design
 - H&MB
 - PFD
 - P&ID
 - System Integration
 - Optimization
 - Engineering Development
 - Anode Gas Handling
 - Hydrogen Purification

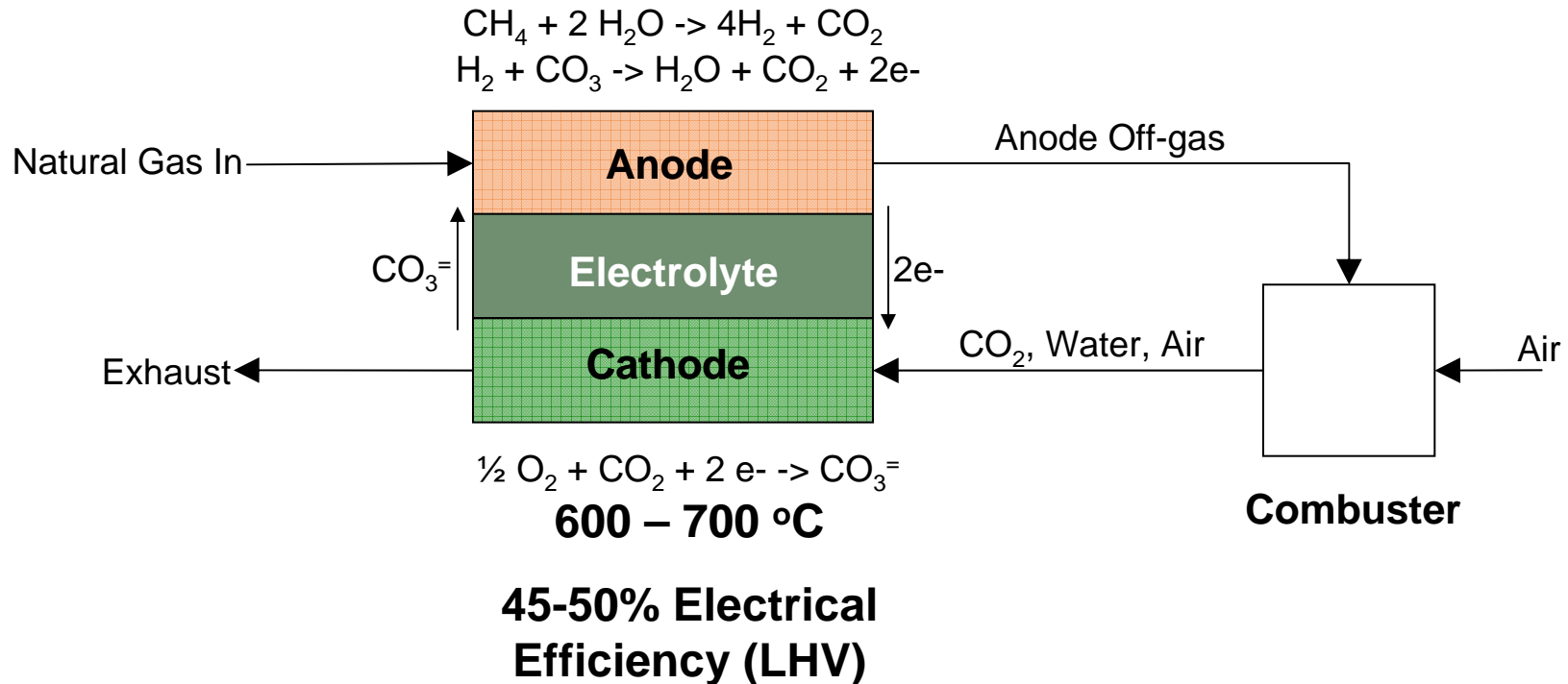
Fuel Cell Selection for the Next Generation Hydrogen Energy Station

- **Selected FuelCell Energy's DFC-300**
 - **Pre-commercial Product**
 - **Utilizes Internal Reforming**
 - **Fuel Cell Energy is Developing Both MCFC and SOFC Technologies**



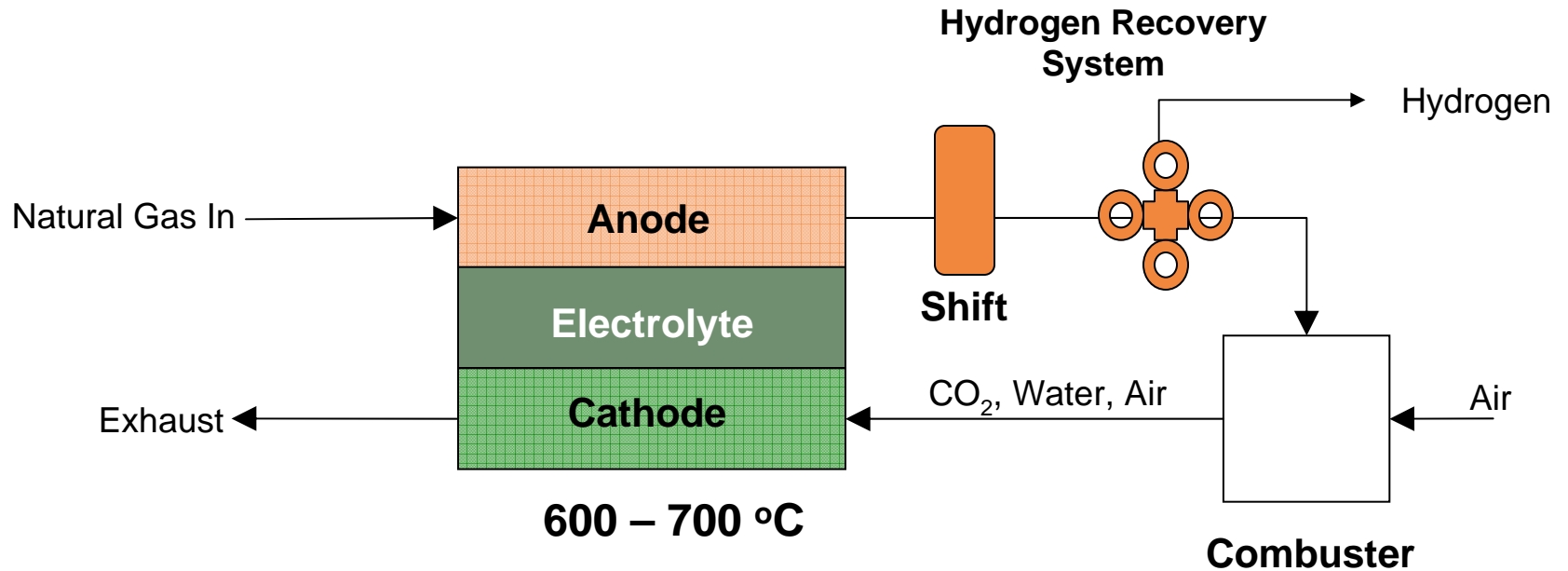
FuelCell Energy DFC-300

MCFC Process (Internal Reforming)



- Anode off-gas contains unreacted hydrocarbons, hydrogen, CO, CO₂ and steam
- Off-gas is combusted and CO₂ is recycled to Cathode- MCFC requires CO₂ on the Cathode side

MCFC Process for Co-Production



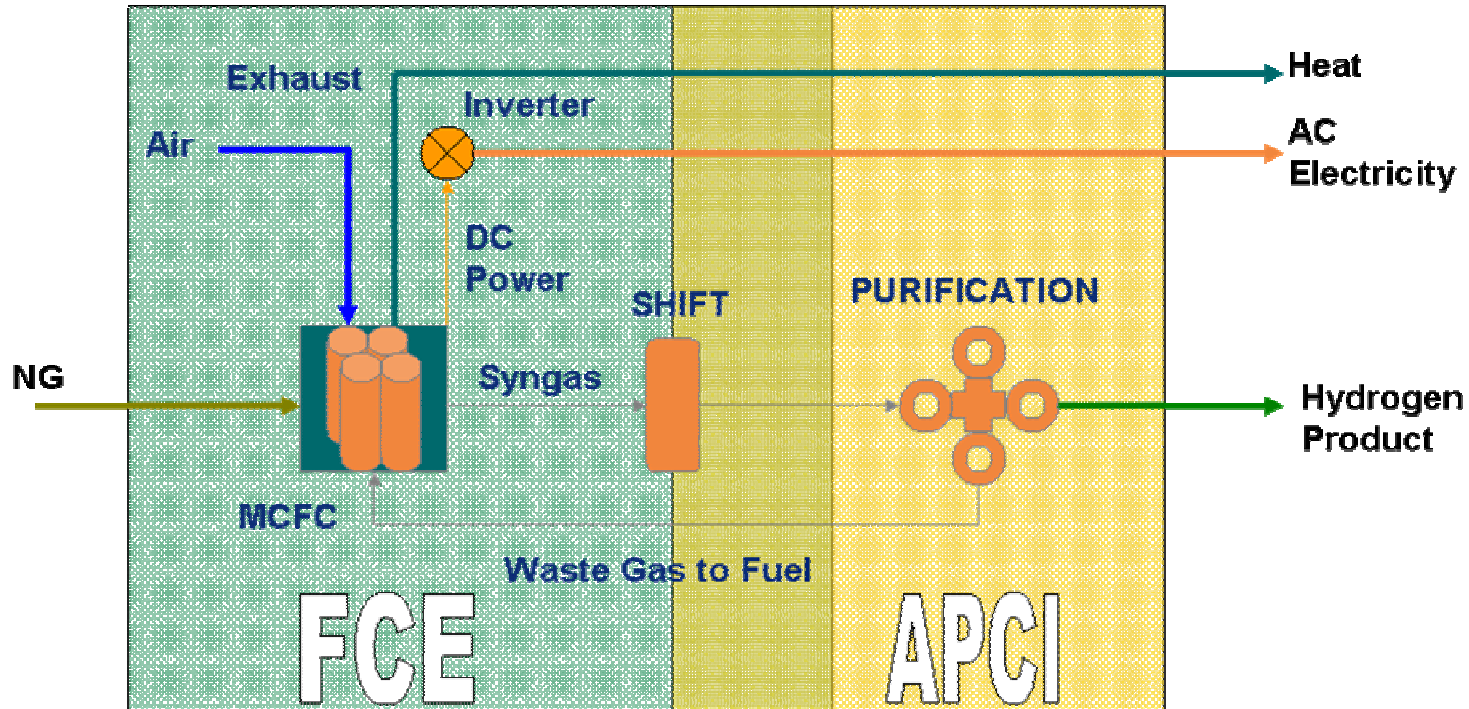
55 - 60 % Co-Production Efficiency (LHV)

$$\text{Efficiency} = (\text{Net Elect. Power Out} + \text{LHV of Hydrogen}) / \text{LHV of Natural Gas}$$

Projected Performance

| | Units | Value |
|--|--------|--------------------|
| Overall Efficiency (Net Power + Hydrogen Product) / (Fuel) | LHV | 60% |
| Power Efficiency Net Power / (Total Fuel – Hydrogen Product) | LHV | 49% |
| Hydrogen Efficiency (Hydrogen Product – Purification Power) / Hydrogen Product | LHV | 68% |
| | | |
| Hydrogen Product | Nm3/hr | ~ 40 |
| Net Power w & w/o Hydrogen | kW | ~ 247 / 207 |
| Natural Gas Flow | Nm3/hr | ~ 55 |

Hydrogen Energy Station Engineering Development Activities



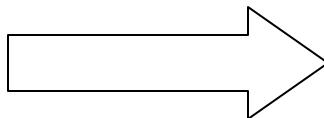
Engineering Development Required:

- Recovering and conditioning off-gas
- Purification of hydrogen
- System integration
- Optimization of co-produced products

Hydrogen Coproduction Challenge

- **Start- Anode Outlet**

- H₂: 10%
- H₂O: 40%
- CO: 5%
- CO₂: 45%
- High Temperature
- Low Pressure



- **Product- Hydrogen**

- > 99.99 % H₂
- < 1 ppmv CO
- > 100 psig

- **Subject to Economic Balance:**

- Capital
- Hydrogen Recovery
- Parasitic Power
- Heat Recovery
- Water Recycle
- Waste Gas Integration

Engineering Development: Anode Gas Processing

- **Anode Piping Modifications**
- **Heat Integration**
- **Water Handling**
- **Low Pressure Gas Handling**
 - **Heat Exchangers**
 - **Shift Reactor**
- **Integration Pre and Post Purification**
- **Cycle Optimization with Purification**

Engineering Development: Hydrogen Recovery

- **Challenges**
 - **Low Pressure Stream**
 - **Very Low Hydrogen Partial Pressure**
 - **High Purity Hydrogen Product at Pressure**
 - **Minimize Parasitic Power Usage**
- **Air Products Solution**
 - **Evaluated > 25 Purification Concepts**
 - **Down selected to a handful of near term options**
 - **Selected an Adsorption Based Process**
 - **Novel Adsorbent Materials**
 - **Novel Cycle Tailored to the Application**

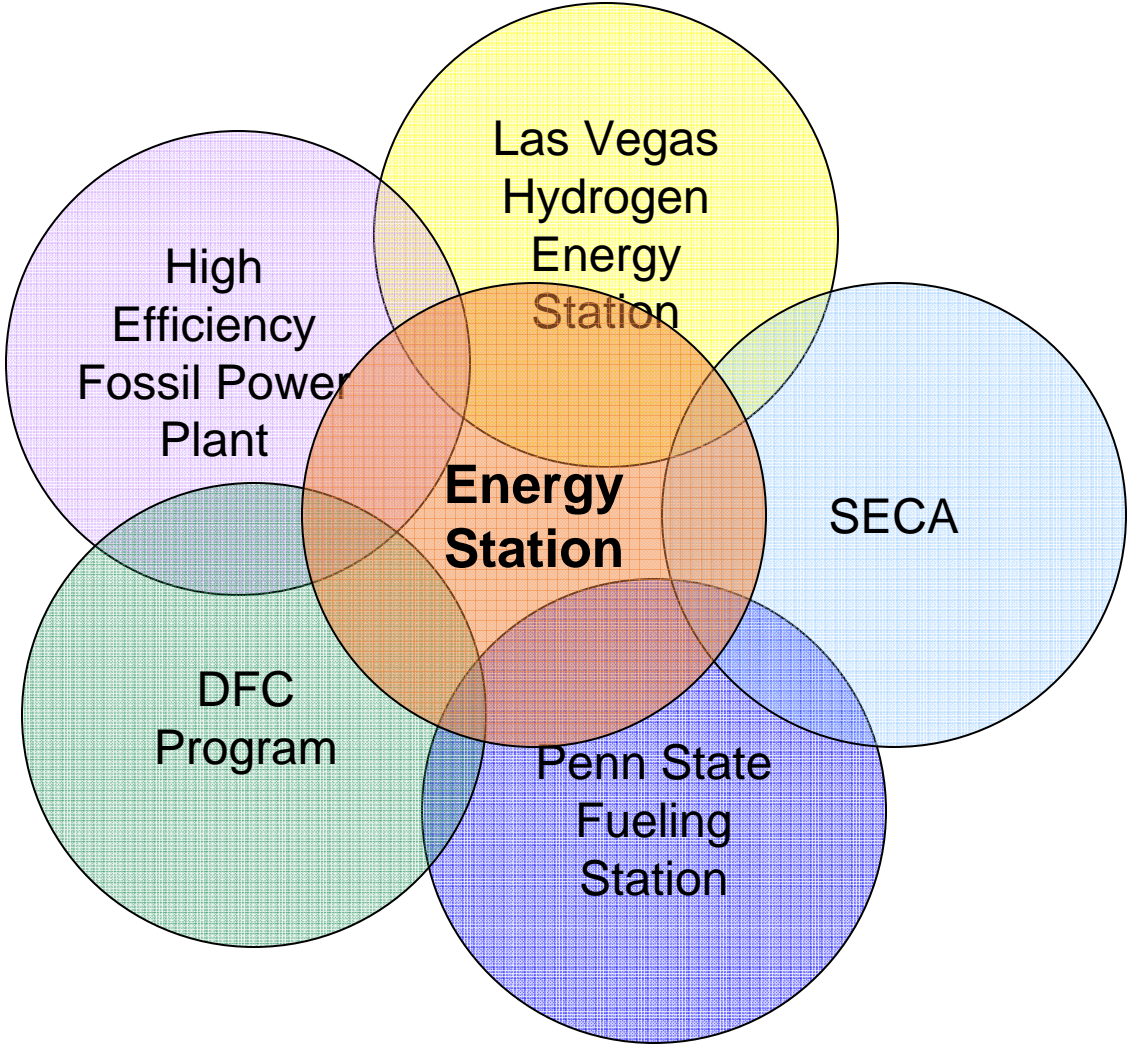
Future Work

- **Remainder of FY 2005**
 - Complete Engineering Development Work
 - Finalize Design
 - Update Economics and Demonstration Cost Estimate
 - Go / No- Go Decision for Demonstration
 - Secure Funding for Demonstration Phase

- **FY 2006**
 - Purchase Equipment
 - Equipment Fabrication and Construction
 - Installation
 - Start-up

- **FY 2007**
 - Operation
 - Testing
 - Data Collection

Innovation



Reviewers Comments

- **Include a Demonstration in the Next Phase**
 - Demo is planned pending Go / No-Go and funding
- **Address how H₂ off-gas would be recovered from High-Temp Fuel Cell**
- **Collaboration**
 - Phase 1 – Fuel Cell Companies, Universities
 - Phase 2 – FuelCell Energy
 - Phase 3 – Additional:
 - Universities
 - Energy/Utility Companies

Thank you

Special Thanks to:

DOE- Sig Gronich, Chris Bourdeaux

FuelCell Energy- Pinakin Patel, Fred Jahnke

Air Products- Todd Carlson, Dave Guro

Publications / Presentations

- **DOE Annual Review Meeting – 2003-2004**
- **Mentioned in Presentations at:**
 - DOE Regional Meeting in Annapolis, MD - 2004
 - NHA Annual Meeting – March 2005
 - SAE Annual Meeting – 2004
- **NHA Annual Meeting Presentation – March 2005**
- **SAE Annual Meeting – May 2005**

Hydrogen Safety

- **The most significant hydrogen hazard associated with this project is:**
 - *This is a comprehensive project which may include the operating demonstration of an integrated hydrogen generation, hydrogen refueling, and electricity cogeneration station. As such, several potentially hazardous situations are possible and will be covered in Air Products' safety and design reviews. A detailed HAZOP will identify the hazards and the safety measures to be taken to mitigate them.*

Hydrogen Safety - Approach

- **Our approach to safety issues is comprehensive and is based upon a tremendous experience base**
- **Safety**
 - APCI has >40 years experience in safe design, construction, & operation of H₂ plants.
 - PHR: Phase 2
 - HAZOP: Phases 3 & 4
 - All applicable industry codes are followed
 - APCI participates in SAE, ICC, ISO, HFPA, IETC, and EIHP2 committees.