

Low-Cost Hydrogen Distributed Production System Development

Frank Lomax, Ph.D., P.E. – Principal Investigator

C.E. Thomas, Ph.D., Maxim Lyubovsky, Ph.D., Rick Todd, Ph.D., Chris Van
Dyke, Ed McCullough, Nick Sazdanoff

H2Gen Innovations, Inc.

May 15, 2007

PD2

Overview

Timeline

- Start: July 1, 2005
- End: June 30, 2008
- ~55% Complete

Budget

- Total project funding
 - \$3.46M DOE funds
 - \$1.89M contractor share
- \$450,000 in FY05
- \$400,000 in FY06
- \$2.6 million in FY07

Barriers

- Fuel Processor Capital Costs.
- Fuel Processor Manufacturing
- Operation and Maintenance (O&M)
- Feedstock Issues.
- Control and Safety

Partner

- Süd-Chemie

Objectives

Execute on the following specific goals as part of the overall plan to overcome the barriers identified by the USDOE and to meet the USDOE technical targets in terms of cost and energy efficiency

- **Primary Objective:** Design, build and test a 565 kg/day distributed natural gas hydrogen plant producing 99.999% pure hydrogen to meet the 2010 DOE hydrogen cost target of \$2.50/kg
- **Secondary Objective:** Develop a catalyst suite through lab testing based on our current technology suitable for use with fuel grade ethanol to facilitate renewable hydrogen production

Hydrogen Plant Approach

First steps – analysis and bench scale experiments

- Catalyst improvements - done
- Balance of plant improvement - done
- Advanced reactor design - done

Second step - integration and test improved technology in the existing HGM-2000 platform

1. Incremental improvements - done
2. Obtain long-term test data (eventually in commercial test fleet) - done
3. Make ongoing progress towards USDOE goals - done

Final deliverable

1. Design 565 kg/day plant using DFMA, FMEA and other best practices based on lessons learned from second step – done
2. Construct first 565 kg/day plant – done
3. Test first 565 kg/day plant
4. Redesign 565 kg/day plant based on test results and DFMA
5. Test second 565 kg/day plant

Ethanol Approach

Change in approach from original program

- Pre-reforming to create CH₄ stream from ethanol fuel feed followed by an H₂Gen CH₄ reforming process
- Use H₂Gen pre-reforming process developed for commercial LPG reforming to handle heavy feed constituents (US Patent pending)

Test catalysts on absolute ethanol (clean rectificate, low water)

- Screening tests ~ 100 hours to optimize operating conditions
- Durability tests over 1,000+ hours

Then – study of the effects of fuel ethanol additives and impurities

- Organic cogeners present in purely rectified fuel grade ethanol
- Stabilizers and corrosion inhibitors added to fuel grade ethanol

Then – demonstrate ethanol reforming durability when operating with real fuel grade ethanol

- Fuel grade ethanol denatured with gasoline
- Partially-refined ethanol containing water (more energy efficient and cost effective?)

Use results to identify and develop needed improvements

- Optimize operating conditions (temperature, space velocity, S:C)
- Optimize catalyst formulation (required variations from LPG pre-reforming catalyst)
- Develop absorption / guard beds to clean poisons / inhibitors from fuel grade ethanol

Accomplishments - reactor

Based on test experience at 113 kg/day scale –
H2Gen redesigned reactor and flowsheet for
565 kg/hr platform

- Low pressure drop burner
- Compact, low stress steam generator
- Linear combustion air supply system

To reduce risk and cost – all three innovations
were tested at full 565 kg/hr scale with
production-intent hardware

HGM 10,000 Burner Test

Engineering calculations and Computational Fluid Dynamics CFD software were used to design HGM 10,000 burner system. Burner test validated design, confirmed complete combustion and even heat distribution.

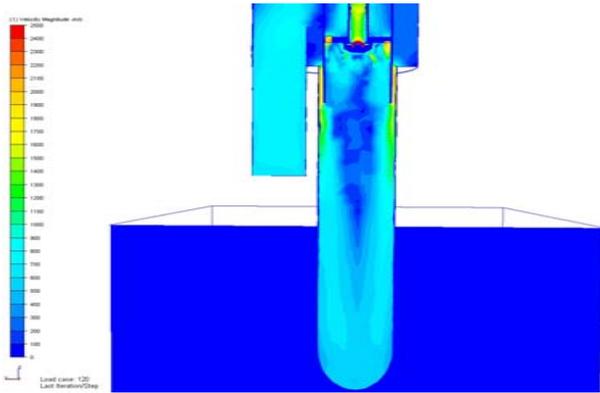


Figure A: CFD Analysis of mixing region for 10K Burner

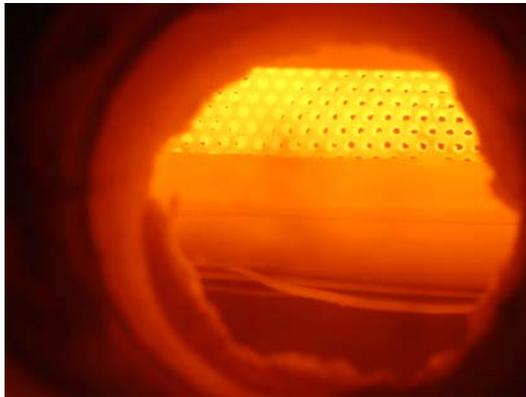


Figure B: HGM 10,000 Burner Test Internal View

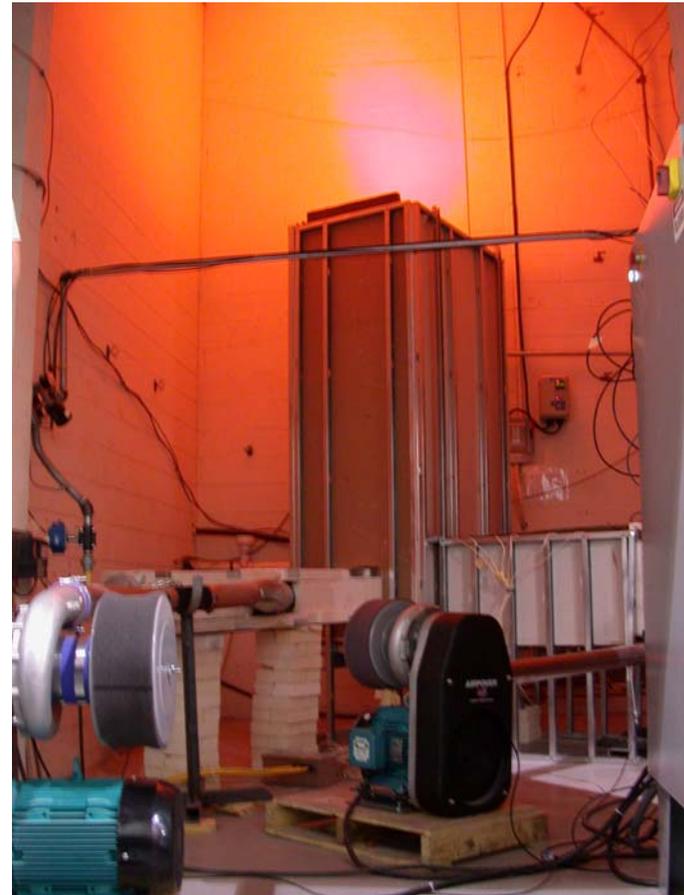
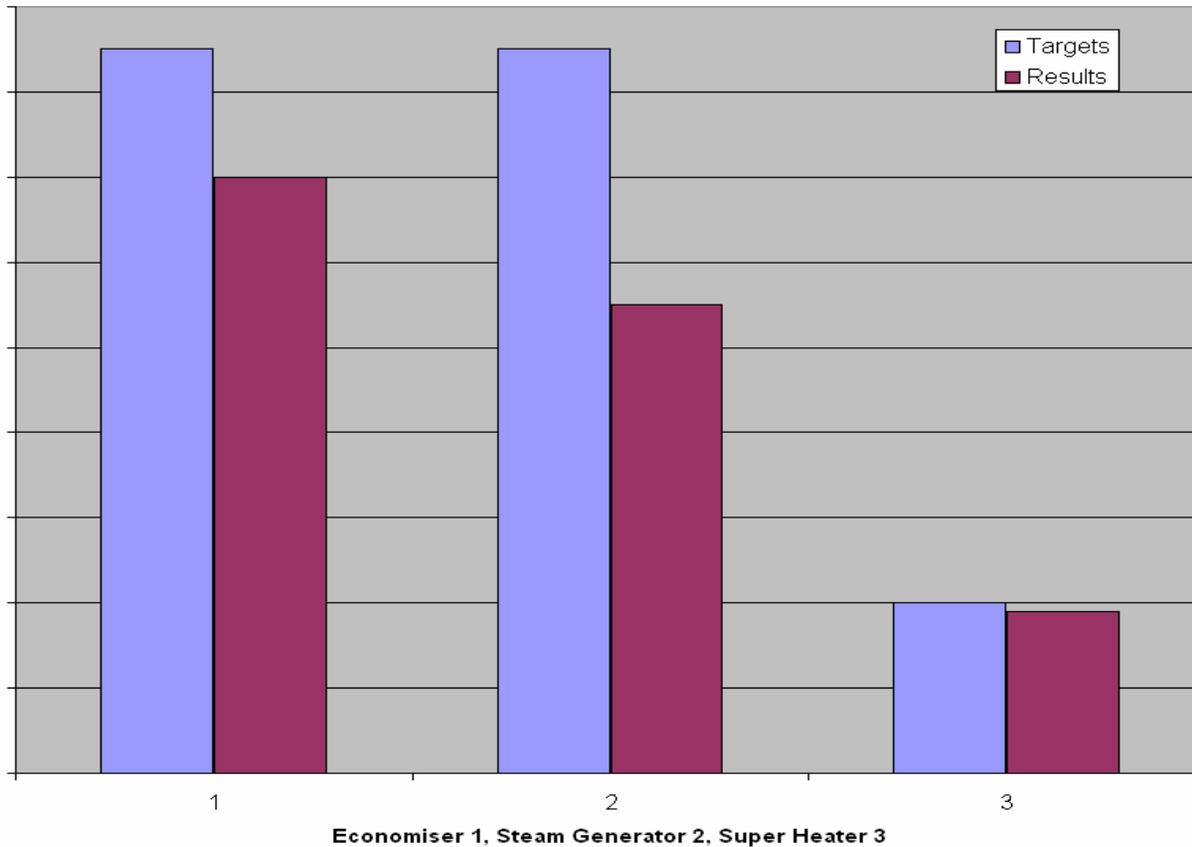


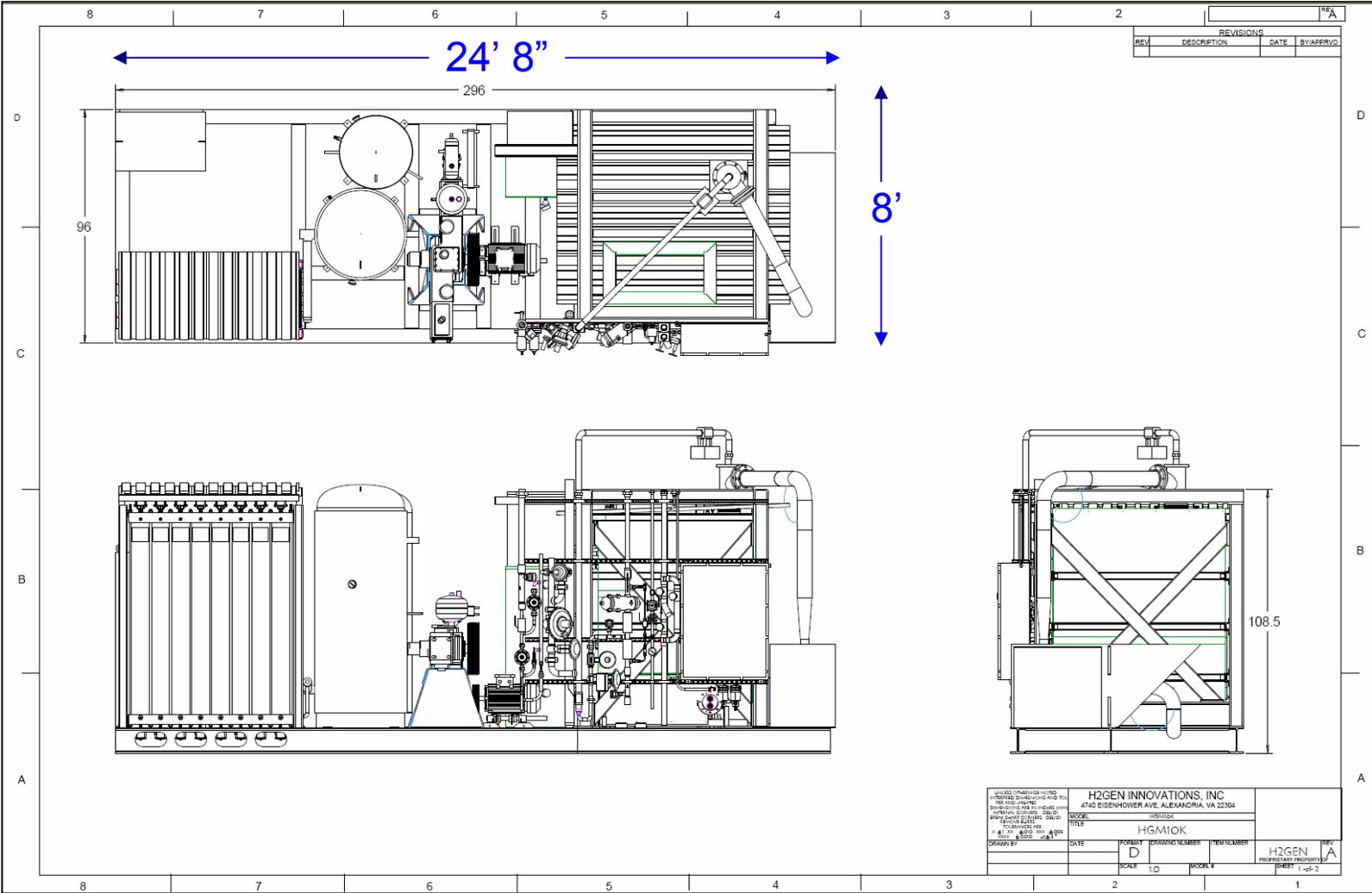
Figure C: HGM 10,000 Burner Test Setup

Steam generator test results

Target vs First Generation Results



HGM 10,000 Layout drawings



HGM 10,000 Construction



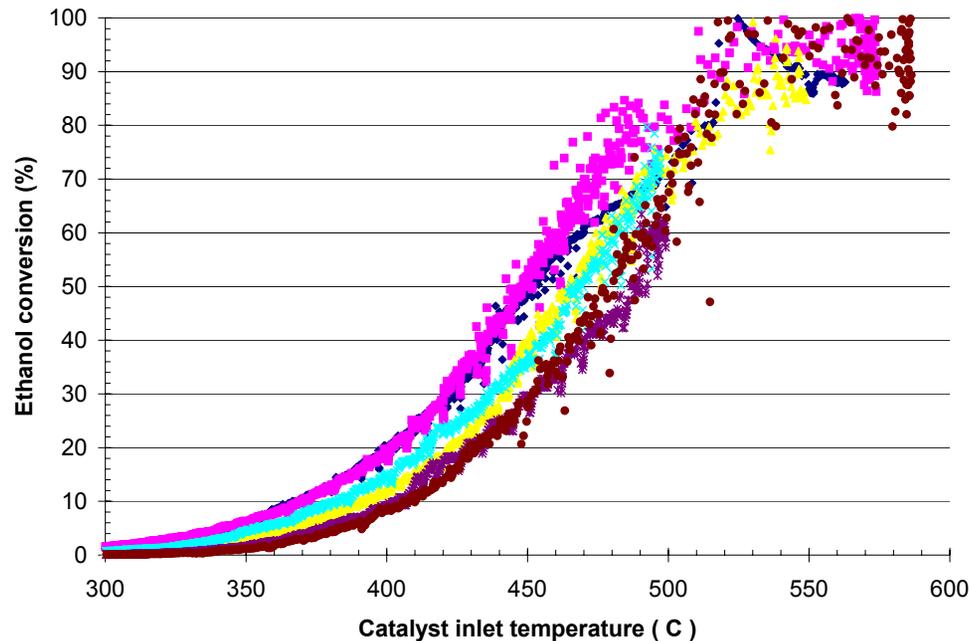
Accomplishments - PSA

- Designed a new, increased capacity PSA with parts commonality to existing 7-vessel PSA
- Constructed PSA's (2 for 565 kg/hr,) developed operating software

Accomplishments – plant level

- Designed skid to industry standards
 - B31-3, VIII-1
 - API 618
 - NFPA 70A, 497, 496
 - CSA 5.99
- Constructed skid, heat exchangers, piping, e-panels, etc.

Ethanol Micro-reactor Test Results



- Absolute ethanol (clean)
- Complete conversion under HGM SMR inlet conditions
- Low sensitivity to conditions variations
- Nearly thermally neutral process (methanation balanced by steam reforming)

Future Work on Primary Objective – Hydrogen plant

- **Test first 565 kg/hr hydrogen plant at field site**
- **Identify areas for improvement based on test data**
- **Key milestone – redesign 565 kg/hr plant**
- **Construct second generation plant**
- **Test second 565 kg/hr plant at a second field site**

Future Work on Secondary Objective – ethanol testing

- **Demonstrate catalyst durability >1,000 hours for reforming rectified ethanol (ongoing)**
- **Select impurities, cogeners and additives components representative of fuel grade ethanol (ongoing)**
- **Test effect of individual components in screening mode (~ 100 hours per test)**
- **Select absorbents / guard beds for components that adversely affect reforming activity**
- **Test real ethanol fuels in durability tests (>1,000 hours per test)**
- **Make go/no-go feasibility judgment based on durability tests**

H2 Cost Projections vs. DOE Goals

	HGM-2000	HGM-10,000	HGM-26,450
Capacity (kg/day)	113	567	1,500
Final Price FOB Alexandria	\$ 173,312	\$ 472,732	\$ 960,234
Total Installed HGM Costs	\$ 225,812	\$ 573,754	\$ 1,111,069
Hydrogen Costs (\$/kg)			
Capital Recovery	1.71	0.78	0.57
O&M	0.47	0.23	0.15
Taxes & Ins	0.03	0.02	0.01
NG fuel	0.78	0.78	0.78
HGM Electricity	<u>0.12</u>	<u>0.12</u>	<u>0.12</u>
H2 Production Cost	3.12	1.92	1.62
Estimated Compression & Storage Costs (\$/kg)			
Capital Recovery	2.06	1.01	0.743
O&M	0.144	0.071	0.052
Compression Electricity	<u>0.11</u>	<u>0.11</u>	<u>0.11</u>
Total Compression & Storage cost	2.31	1.19	0.90
Total Compressed H2 Cost (\$/kg)	5.42	3.10	2.52
Total Compressed H2 Cost (\$/gge)*	2.29	1.31	1.06

Assumptions: H2A compression, storage & dispensing \$\$;
 500 unit production;
 70% capacity factor;
 10% real, after-tax ROI (22.7% annual capital recovery factor)

DOE "All-in" H2 Cost Targets:

2005: \$3/kg

2010: \$2.50/kg

2015: \$2/kg

*On a range-equivalent basis with 2.4X better fuel Natural Gas = \$4.5/MBTU; Electricity =5 cents/kWh

H2Gen: HGM Cost Scaling size and quantity.XLS; Tab 'HGM\$';Q73 - 5 / 4 / 2006



Summary

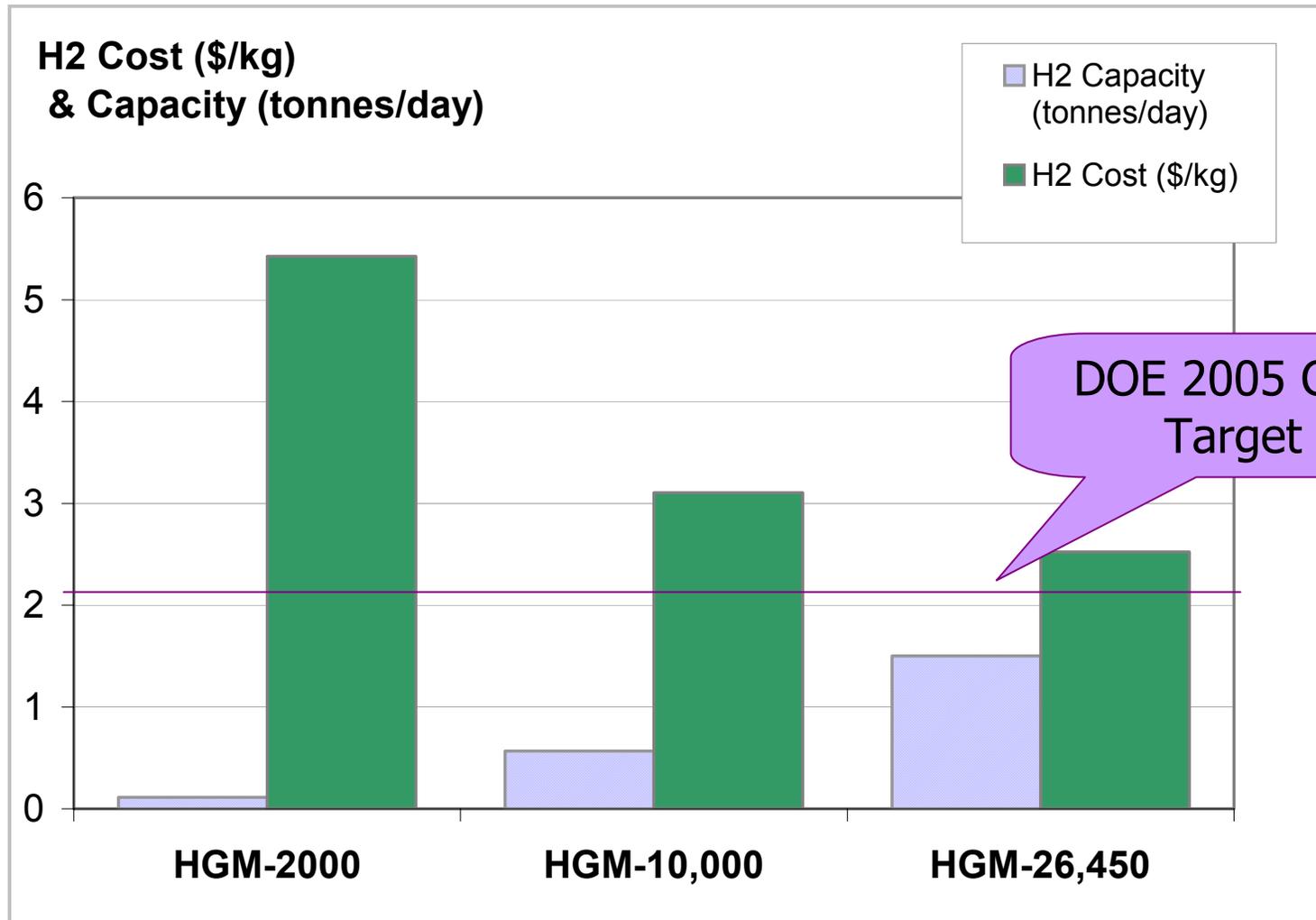
- **Due to budget restrictions during past years, H2Gen refocused project to deliver a 565 kg/hr plant with minimized project budget and risk**
- **H2Gen has completed design, shop testing and construction of this plant – on time and under budget**
- **With expanded budget this year, a second-generation plant is planned which will materially-advance the state of the art based on lessons-learned from the first plant**
- **We have identified partners to provide sites for these plants – thus eliminating significant ongoing expense and facilitating test of a fleet of two plants on an ongoing basis**
- **Despite budget concerns, ethanol work was restarted and significant early progress has been made – we expect to complete ethanol work at an accelerated pace with resumption of project funding**

FY2007 Targets

Distributed Natural Gas Hydrogen Generation Targets			
Production Parameter	Units	System Target	
Hydrogen Output	Kg/day	565	
System efficiency	% LHV	>67.5	
Parts Cost	\$	<\$350,000	
Field test time	hours	2,500	
Ethanol Reforming Target			
Catalyst test time	hours	>1,000	

Additional Slides

Compressed Hydrogen Cost Projections



Natural Gas = \$4.5/MBTU; Electricity =5 cents/kWh

H2Gen: HGM Cost Scaling size and quantity.XLS; Tab 'HGMS';Y87 - 1 / 12 / 2006

Natural Gas Price Impact on H2 Cost

