VI.C.2 Hydrogen Power Park – Business Opportunities Concept Project

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Energy CS, California
John Boyle Consulting, Pennsylvania
Jadey Productions, Arizona
Kinetics, Arizona
US Filter, Arizona
Arizona Machine & Fabrication, Arizona
Air Liquide of America, Arizona
Rocky Mountain Cummins, Arizona
Simplex-Grinnell, Arizona
Arizona Valve & Fitting, Arizona
Omni Engineering, Arizona

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Projected End Date: December 2006

Objectives

- Create conceptual models for Hydrogen Power Park applications.
- Validate park components, performance, efficiency, safety, reliability, quality, and cost.
- Refine conceptual models based upon test results.
- Identify the value propositions.

Technical Barriers

This project addresses many of technical barriers by testing, integration, and operation of equipment from the Technology Validation section (3.5.4.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(C) Hydrogen Refueling Infrastructure
(D) Maintenance and Training facilities
(E) Codes and Standards
(H) Hydrogen from Renewable Resources
(I) Hydrogen and Electricity Coproduction

Contribution to Achievement of DOE Technology Validation Milestones

This project will contribute to achievement of the following DOE technology validation milestones from the Technology Validation section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 19:** Complete Power Park Demonstrations and Make Recommendations for Business Case Economics.

Accomplishments

- Identified value proposition and implemented at two sites, creating annual savings of $90K/site.
- Tested Proton 318 scfh and 220 scfh electrolyzers.
- Tested hydrogen (H2) internal combustion engine (ICE) gensets.
- Tested 3–5 kW Plug Power fuel cells.
- Performed 505 hydrogen fueling events on hydrogen fueled vehicles.
- 1,550 days of continuous operation at pilot hydrogen park with zero accidents in an integrated park operation in real-world setting with hundreds of individual components.
- 9,000 kg of hydrogen produced in hydrogen park application.
- Electricity produced with hydrogen fueled H2 ICE gensets and fuel cells.
- Completed quantitative integration of solar photovoltaic (PV) and biomass renewable energy for hydrogen production.
- Initiated general public access to the pilot hydrogen park in downtown Phoenix.

Introduction

A power park is a potential pathway for hydrogen implementation in society, whose functions create an integrated system of hydrogen production, renewable energy, electricity production, and vehicle fueling. This Arizona Public Service (APS) project focuses on "real-world" equipment and performance by integrating components into the APS Pilot Hydrogen Park. The performance of these components can then be monitored over time to establish their durability and performance. These "learnings" can then be used to identify value propositions, which lead to "business opportunities". The Pilot also has facilitated communication with local building authorities on code issues that provides insight into constructing power parks in communities. The Pilot has a perfect safety record with more than 11,700 credit card fueling events and 9,000 kg of hydrogen produced, and a good relationship with local code officials. Can a hydrogen power park, in certain circumstances, offer a value proposition to potential customers creating an advantage over the "status quo"?

Approach

There are four phases to the approach:

Phase I. Create Conceptual Models
Phase II. Validate Hydrogen Power Park
Phase III. Refine Conceptual Models
Phase IV. Identify Value Propositions

Results

The results of the project are summarized in the following based upon the four required functions of a hydrogen power park. Four candidate power park models were identified (Phase I). The component, equipment and systems performance testing and validation (Phase II) are almost completed. Based upon the performance testing, the original models have been evaluated as to their practical near-term potential to create a value proposition. Where opportunities exist, the models have been refined (Phase III). In one application, a value proposition was identified and installed (Phase IV). The project goal is to identify the value proposition leading to "business opportunities".

Phase I

Four conceptual hydrogen power parks were created with their equipment and systems. They were as follows:

- **Model 1.** 1–10 H2 kg/day system with 5 kW fuel cell, PV array, isolated/grid connected.
- **Model 2.** 20–100 H2 kg/day system with 30–100 kW, PV array, grid connected.
- **Model 3.** 400–1500 kg/day system with 400 kW–5 MW, PV array, grid connected.
- **Model 4.** Mobile distributed power up to 100 kW.

Phase II

Hydrogen Production

During the project duration, three Proton membrane electrolyzers were purchased for the purposes of distributed hydrogen production. A total of 9,000 kg (3,726,000 scf) has been produced by these electrolysis units. Performance testing demonstrated that low production rates (lower electric currents) yielded higher efficiencies on these electrolysis units. The efficiency of these units is 40%, and 41% for the larger 318 scfh and 220 scfh models (6,056 kg/yr and 4,190 kg/yr), respectively, at full output. This compared unfavorably to the DOE goal of 65%. This poor efficiency was offset by excellent availability of 99%, excellent product quality of 99.9997% purity and excellent safety. Maintenance issues with these units were fairly minor covering areas of leaking water lines, pump impeller replacement, combustible detector calibration and a pin-hole in a membrane in the new stack.

Hydrogen was also provided by Air Liquide and Praxair in tube trailers (jumbo – 120,000 scf, and small – 40,000 scf) under a commercial bulk delivery contract. The quoted cost of commercial bulk hydrogen delivered is $18 per kilogram. The actual cost tends to be higher than the quotes. The industrial gas companies ship liquid hydrogen into Phoenix from California and New Orleans and then truck it in tube trailers to their customers.

An electrolysis system requires water treatment and a dryer. The water treatment system uses little electricity, but wastes considerable water (reverse osmosis) with an efficiency between 6–9% (water usage), yielding unfavorable performance. Actual water usage by the electrolysis unit is 2.38 gallons per kilogram. Water treatment systems cost about $6,500 for the 220 scfh unit, with water costs at about $0.016/gal. The desiccant hydrogen dryer has performed well, with an efficiency of 92%. The desiccant has been replaced once in 4 years. Over the 1,550 continuous days of operation and hydrogen production with the 318 scfh unit, water treatment and dryer power consumption average 81 kilowatts hour per kilogram of hydrogen.

Novel Hydrogen Production - SRT Hydrogen-Bromide Electrolyzer Testing

SRT Group, Inc. (SRT) delivered an assembled hydrogen-bromide (HBr) electrolyzer rated at 10 kW to Electrolytic Technologies (ETC) for performance evaluation. The electrolyzer was disassembled for a physical inspection, found to be in good condition and suitable for testing. Based on this inspection, the electrolyzer was reassembled and installed onto a purpose-built test fixture to verify its hydraulic integrity. This testing indicated that the electrolyzer was leak-free and suitable for performance testing.

The first phase of performance testing was designed to operate the 10 kW SRT electrolyzer stack in the hydrogen generation (i.e. "forward") mode to determine its energy and current efficiency for use as a hydrogen generator. Throughout testing, the electrolyzer operated very well at test temperatures up to 50ºC, with no liquid leakage.

Figure 1 presents cell voltage versus HBr concentration for the various current densities evaluated. In this set of test runs, the electrolyzer was operated at a predetermined set of applied amperages to obtain data on the electrolyzer voltage performance as a function of current density vs. HBr wt% concentration. Figure 2 presents cell voltage versus current density for the various HBr concentrations evaluated.

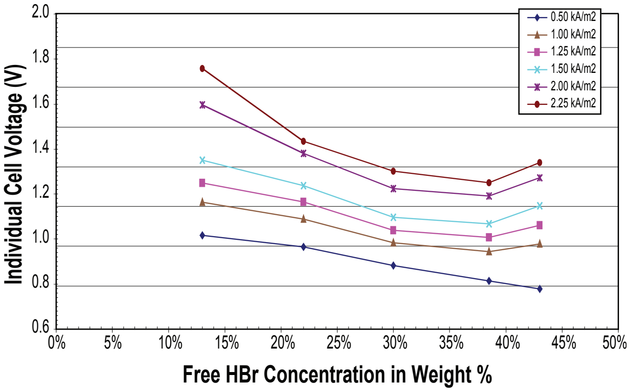

FIGURE 1. Cell Voltage vs Free HBr wt% Concentration at Various Current Densities

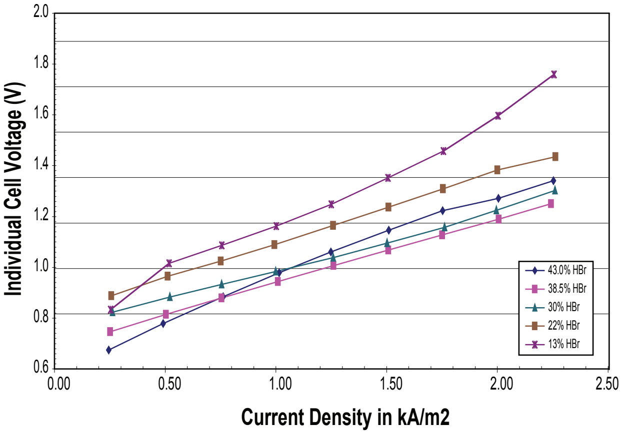

FIGURE 2. Cell Voltage vs Current Density at Various Free HBr wt% Concentrations

Since anolyte bromine concentration can significantly affect the electrolyzer cell voltage, a sequential set batch run was conducted to determine the hydrogen generation current efficiency change as a function of increasing bromine concentration. Figure 3 presents changes in the electrolyzer bromine current efficiency with increasing anolyte bromine concentration, at an operating current density of 2.0 kA/m2. In this test, a batch run with a starting concentration of 42% HBr, containing 1.7 wt% bromine was electrolyzed in four current efficiency runs, ending up with 32% free HBr and 28 wt% bromine. As can be seen from the graph, the current efficiency dropped from about 93% to 56%.

As can be seen from Figures 1 and 2, a minimum cell voltage of 1.2 volts/cell is obtained with an HBr concentration of 38.5% when current density is at a significant level (2 kA/m^2). This is well below the voltage required to electrolyze water. However, it is significantly greater than the 0.7 volts/cell claimed by the electrolyzer manufacturer, SRT. With current density at a more modest 0.5 kA/m^2, the cell voltage approached the 0.7 volts/cell claimed by SRT.

In the second phase of performance testing, the 10 kW SRT Electrolyzer Stack was set up in a power generation configuration. In the "reverse" (i.e. power generation) mode, the electrolyzer module did not generate significant power. After several runs with similar results, the testing was halted. The failure to generate power was deduced to be the result of three possible problems: a) the SRT electrolyzer may not have been assembled with a platinum catalyst; b) that the catalyst had not been prepared properly if it was present; or c) ETC had not correctly connected and operated the electrolyzer. In as much as the third deficiency could be evaluated and corrected in situ, this was done. Although Phase testing in the forward mode (bromine

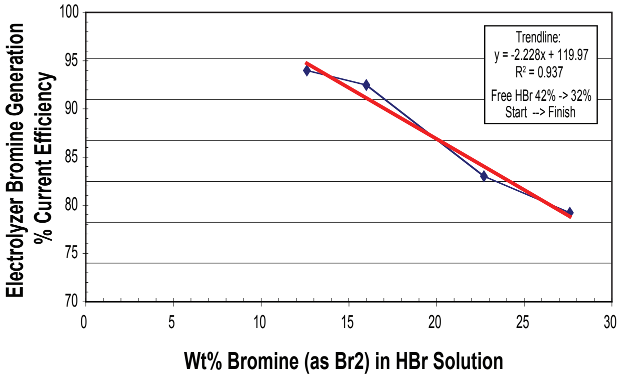

FIGURE 3. Electrolyzer Sequential Batch Hydrogen Generation Current Efficiency with Increasing Bromine Concentration Operating at $2kA/m^2$

production) indicated correct connection and operation, the electrolyzer was flushed, removed from the test setup and disassembled. The inspection showed that the cell had been connected properly. As an additional test, the electrolyzer that had been successfully tested hydraulically was subsequently installed in the test setup and operated for a short period in the forward mode to condition the electrolyzer. Its operation in this mode was nominal. However, when operated in the reverse (power generation) mode, this electrolyzer produced less than 20 DC watts, also indicative of no significant power generation. Consequently, the failure to generate significant power in the reverse mode is most likely due to either a) the SRT electrolyzer was not assembled with a platinum catalyst; or, b) that if there is a platinum catalyst, it had not been prepared properly.

In summary, the 10 kW SRT electrolyzer performed well in the forward mode, producing hydrogen and bromine from HBr at rates consistent with those reported in relevant literature and, at modest current densities, consistent with those reported by the manufacturer. The theoretical cell voltage for water is 1.23 V/cell, while experimental voltages are typically 1.7 to 2.0 V/cell. Hence, the SRT cell compares favorably at low current densities to water electrolyzers. It appears that an issue with the catalyst is preventing similar performance in the reverse mode, consuming bromine to produce power.

Electricity Production

The APS Pilot Park has produced 51 MWh of electricity from fuel cells, H2 ICE gensets and its PV array. A total of three 5 kW fuel cells were tested which consistently demonstrated a net fuel cell efficiency of 46% (fuel cell displayed efficiency was 56%). Operating life of the units has varied from 800 hours to 4,500 hours of stack life. Experience with the Plug Power fuel cells has indicated limited nameplate power output and continuous operation at 60% of nameplate is preferred.

Internal combustion engines were evaluated as an alternative to electricity from fuel cells. Two groups were evaluated; 1) gensets, and 2) automotive engines. Both of these groups were evaluated with hydrogen and hydrogen/natural gas blends. The gensets tested had engines manufactured by Cummins and Lister Petter. These commercial heavy-duty engines have 40,000 operating hours between overhauls. The automotive engine tested was a Ford 5.4L V8, massed produced, low-cost, with an estimated life of 5,000 hours. Using hydrogen fuel resulted in a derating of unmodified heavy-duty engines to about 60% of nameplate; full power rating was achieved on the hydrogen natural gas blends. The heavy-duty engines produced low oxides of nitrogen (NOx) emissions and efficiency of 28% which is comparable to operation on natural gas and propane.

Renewable Energy

The APS Pilot Hydrogen Park installed a 6 kW flat plate solar array. The installed cost of this array was $72K. APS has extensive performance data from solar energy collected from its STAR Center (Solar Test and Research) over the past 30 years.

Vehicle Fueling

The APS Pilot Hydrogen Park is located in downtown Phoenix. It is accessible to the public, who can purchase fuel with a credit card transaction, similar to what occurs at a conventional gasoline fueling station. There are four basic fuel types available at the Pilot Park; hydrogen, CNG (Compressed Natural Gas), blends of hydrogen and natural gas (15%, 20%, 30%, 50%), and electricity. Vehicle fueling has been ongoing for more than four years. During that period, there have been 11,736 vehicle fueling events composed of 573 hydrogen fueling events, 4,069 blend hydrogen fueling events, and 7,094 CNG fueling events.

Fuel cell vehicle prototypes from both DaimlerChrysler and Nissan have fueled at the station. No problems were encountered during these fueling events. These manufacturers require hydrogen purity certification prior to refueling. Hydrogen purity certification was provided by a local lab, which confirmed purity at 99.9997%.

The majority of hydrogen fueling is to H2 ICE powered vehicles, which consist mostly of local conversions of standard automotive engines. Hydrogen blends have been very popular with many commercial taxis cabs (dedicated CNG) and the general public using 15% hydrogen. Several emission tests were conducted on APS fleet vehicles using 15% and 30% hydrogen. These tests compared variably to new model gasoline vehicle emissions.

The cost of hydrogen must be adjusted for motor vehicle fuel cost. These costs include storage, compression, dispensing and appurtenances. These are long life components and do not pose a significant increase in the cost of hydrogen motor vehicles if amortized over long periods. Some rules of thumb from Phase II results are $20,000/kg for hydrogen compression, $700/kg for storage results in less than $0.50/kg added cost for the ability to fuel motor vehicles.

Phase III

Both the fixed and variable cost to produce hydrogen from small scale electrolysis is provided in Table 1. The cost sensitivity of hydrogen is driven by the electrolysis equipment.

TABLE 1. Cost of Hydrogen Production at Pilot, Grid Electricity, Off-Peak

Electrolysis Original Cost, 5 yr life	Fixed cost per Kg 90% CF	Variable Cost		Total Cost H2
		Energy	Water	
Small Low Efficiency Electrolysis				
$105,000	$3.45	2.261	0.038	$5.749
$130,000	$4.28	2.261	0.038	$6.579
$190,000	$6.23	2.261	0.038	$8.529
Small Electrolysis at DOE Target Efficiency				
$105,000	$3.45	$1.435	$0.038	$4.923
$130,000	$4.28	$1.435	$0.038	$5.753
$190,000	$6.23	$1.435	$0.038	$7.703

The Phase II cost of electricity produced by hydrogen fuel using the Pilot Park equipment is described in Table 2. As can be seen, this cost compares unfavorably to grid and renewable electricity. However, it does compare favorably to seasonal peaking or contingency electricity produced by an electric utility, whose cost is not presented in this report because it is considered confidential.

TABLE 2. Pilot Park Cost of Electricity from Hydrogen-Fueled Fuel Cells and H2 ICE Units

	Fuel Cell	Cummins	Lister Petter	Ford
$/kw	$3,600	$1,000	$2,000	$81
Life	4,500	40,000	40,000	5,000
After Tax $/kw	$2,160	$600	$1,200	$49
Fixed Cost $/kwh	$0.48	$0.015	$0.03	$.02
Efficiency	48%	28%	28%	40%
Kwh/Kg H2	16.03	9.35	9.35	13.36
H2 $/Kg	$5.75	$5.75	$5.75	$5.75
Variable $/kwh	$0.358	$0.615	$0.615	$0.430
Electricity $/kwh	$0.838	$0.630	$0.645	$0.450

Note: analysis is based upon 8,760 hours per year. One fuel cell covers 51.37% of a year. Capital recovery factor of 23%. Production using the $105K Proton 220 scfh unit.

All renewable energy is reduced to the retail cost of electricity from a source, using a variety of technologies (includes both variable and fixed cost). Considerable effort, time, and investment were necessary to produce this data base. The cost data is submitted in this report in the following table reflects both the APS Pilot Park efficiencies and the DOE Target (see Table 3). The APS Pilot installed a fixed horizontal array which produces electricity at $0.22/kWh, although typically the APS installation would be hundreds of kW enjoying economies of scale. The APS rate for summer "on-peak" electricity is $0.13310/kWh. This highest cost grid electricity compares favorably to all of the renewable choices except for biogas from municipal waste water operations, which is a very limited resource.

TABLE 3. Cost of Renewable Electricity by Technology and Resulting Cost of Hydrogen

Renewable	Capital $ $/kw	Annual Energy kWh/kW-yr	Energy Cost $/kwh	H2 Energy Cost $/kg	
				41% Eff	65% Eff
PV Fixed Horizontal	5,250	1,250	$0.220	$17.82	$11.31
PV Fixed Latitude	5,250	1,630	0.171	$13.85	$8.79
PV Tracking Horizontal	5,500	2,350	0.127	$10.29	$6.53
PV Tracking Latitude	6,500	2,450	0.131	$10.61	$6.73
PV High Concentration	6,000	2,030	.158	$12.80	$8.12
Organic Rankin Cycle Trough	4,000	2,000	0.130	$10.53	6.68
Forest Products	$3,000	NA	$0.120	$9.72	$6.17
Biogas Municipal Waste	$2,000	NA	$0.08	$6.48	$4.11
Biogas Ag. Cattle	$3,000	NA	$0.14 – 0.17	$12.00	$8

It can be concluded that by using solar energy sources, that the cost of hydrogen will be substantially greater than if grid electricity is used for electrolysis production of hydrogen. In all likelihood, the best application from solar is to feed the grid with electricity. However, if in some circumstances excess solar energy were available, the marginal cost of solar is about $0.01/kWh, which would provide a very low-cost energy source. Further, in research performed at the APS STAR facility, silicon PV cells do not fail from aging, although their performance does deteriorate over time. Hence, we have not ascertained the life of silicon PV cells, but it appears to be greater than 50 years. The APS costs do not reflect this long potential life.

Real issues facing the Conceptual Hydrogen Power Park Models are as follows. The large commercially available electrolysis units do not lend themselves well for incorporation into renewable or grid systems. New types of electrolysis equipment must be competitive and commercially offered that address both grid and renewable power issues. PEM fuels cells are expensive, small, and the life performance is questionable. H2 ICE has demonstrated potential viability, but viable commercial product offering is lacking. And, finally, there are no hydrogen fueled cars, only prototypes and third-party conversions.

If the primary goal of a hydrogen park is to undercut the price of gasoline with hydrogen, then this project concludes it can't be done at this time. If the goal of a Hydrogen Park is to undercut the price of electricity using hydrogen and fuel cells, then this project concludes it can't be done at this time. However, this project does conclude there appears to be very viable business opportunities now for elements of a hydrogen park in certain niche applications. If additional reliable commercial equipment were available, more applications appear viable. If the cost of small electrolysis units was significantly less and were reliable, greater opportunities would exist. Large electrolysis units, in a higher demand market, are anticipated to compare economically favorable to the data from the small electrolysis system in Phase II of this project. If policy or government financial incentives were available, then a better opportunity would exist for hydrogen to compete as a motor vehicle fuel. Without policy, financial incentives, or creditable equipment, then the business opportunities are substantially reduced to two simple criteria, 1) a need for hydrogen, and 2) distance to a large steam methane reformer.

Phase IV

Two satellite hydrogen production systems were installed. The characteristic which created this value proposition was the distance from the nearest commercial steam methane reforming (SMR) unit. Due to the small number of these large SMR plants, numerous potential business opportunities exist. Because the need for hydrogen cost justifies the investment in water treatment, cooling, and electrolyzers, the cost of hydrogen for other applications is now calculated on marginal costs, (i.e., electricity and water). This results in a substantial reduction in the cost of hydrogen, and as shown above currently compares favorably to the cost of petroleum fuels. Hence, the production of backup electricity is potentially on parity with existing alternatives, if H2 ICE gensets are used.

Additional equipment such as compressors, storage vessels, and fuel dispensers (assuming vehicle refueling is desired) can be amortized over long periods due to their useful live. If the primary use of hydrogen absorbs the capital or fixed cost associated with hydrogen production, then the marginal cost of hydrogen for use as fuel for standby electric generation is \$2.30/kg plus an allowance for maintenance (from Phase II data using Proton electrolyzers and APS off-peak electric rates), and the cost of hydrogen motor vehicle fuel is \$2.80/kg plus an allowance for maintenance. These costs compare favorably to the selling price of petroleum fuels, and compare unfavorably to the cost of natural gas (about \$1.30/gge average cost in 2006 without CNG fixed cost and maintenance).

Conclusions and Future Directions

a) The Phase II validation process confirms hydrogen power park functions are feasible and safe.

b) The biggest barrier facing hydrogen produced by small distributed electrolysis units is the cost of the electrolysis equipment. Higher energy efficiencies would improve the cost, but longer life and less costly electrolysis equipment would generate more favorable economics.

c) Small distributed electrolysis unit costs compared favorably to hydrogen delivered by commercial industrial gas companies, where the delivery point is some distance from the central steam methane production plant.

d) Hydrogen produced by small electrolysis units represents no hazard to the public and can be constructed within existing codes.

e) Electricity produced from H2 ICE gensets compares favorably to electricity from PEM fuel cells.

f) Phase II work concludes that PEM fuel cells have short lives and high costs.

g) Phase II and III work concludes that electricity from hydrogen power parks will be higher than existing electric rates.

h) The cost of hydrogen will be greater if solar energy is used to produce the hydrogen via electrolysis rather than grid power.

i) The total cost of hydrogen from electrolysis is a greater expense than petroleum fuels today.

j) Hydrogen can be used as a motor vehicle fuel and it will be more costly than today's petroleum alternatives.

k) The Hydrogen Power Park has the best opportunity to provide a value proposition when hydrogen is needed and the existing commercial source of hydrogen is some distance from its point of use.

Special Recognitions & Awards/Patents Issued

1. "*Crescordia*" (growing in environmental harmony) from the Phoenix Area Valley Forward Association, September 2003.

2. U.S. Department of Energy, 2004 Clean Cities Recognition, May 2004.

3. Recognition by New Mexico Hydrogen Business Council, February 2005.

4. Clean Cities Champion Award for "Advanced Technologies", February 2005.

5. Clean Cities "Arizona's Road to Clean Air & Energy Security" Champion, February 2006.

FY 2006 Publications/Presentations

1. US DOE Annual Program Review presentation, May 2006.

2. UNLV Hydrogen Safety Lessons Learned presentation, April 2006.

3. National Hydrogen Association Annual Meeting presentation, March 2006.

4. Hydrogen Utility Group Senate Caucus Briefing presentation, February 2006.

5. NETL Hydrogen presentation, February 2006.