Manufacturing Research & Development
for Systems that will
Produce and Distribute Hydrogen

Background Material for the Manufacturing R&D Workshop
to be held July 13-14, 2005
Washington, DC

July 7, 2005

Introduction

In his 2003 State of the Union Address, President Bush announced a $1.2 billion Hydrogen Fuel Initiative to accelerate the development of the hydrogen and fuel cell technologies needed to move the United States toward a future hydrogen economy. While many scientific, technical, and institutional challenges must be overcome to realize the vision of a hydrogen energy economy, moving from today's laboratory-scale fabrication technologies to high-volume commercial manufacturing has been identified as one potential roadblock to a future hydrogen economy.

The Workshop

The Federal Interagency Working Group on Manufacturing for the Hydrogen Economy was established to coordinate and leverage the current federal efforts focused on manufacturability issues such as low-cost, high-volume manufacturing systems, advanced manufacturing technologies, manufacturing infrastructure, and measurements and standards. Participants in this working group include the Department of Energy (DOE: lead organization), Department of Agriculture, Department of Commerce/National Institute of Standards (NIST), Department of Defense, Department of Transportation, Environmental Protection Agency, National Aeronautics and Space Administration, National Science Foundation, Office of Management and Budget, and White House Office of Science and Technology Policy. Over the last year, this working group has been laying the groundwork for developing a roadmap to coordinate and guide research and development (R&D) efforts on manufacturing technologies critical to commercializing hydrogen and fuel cell technologies. The *Roadmap Workshop on Manufacturing Technologies for the Hydrogen Economy* is the next step in this process.

The purpose of the Manufacturing R&D workshop is to bring together industry, university, and government representatives to discuss the key issues facing all aspects of manufacturing for hydrogen products including: (1) fuel cells that convert hydrogen into electric energy, (2) hydrogen storage systems, and (3) large-scale hydrogen production and delivery systems. The

recommendations resulting from this workshop, which will outline the key technical problems facing the manufacture of hydrogen systems today and identify priorities for research and development on manufacturing during the transition to a hydrogen economy (e.g., 2005-2025), will be incorporated into the *R&D Roadmap on Manufacturing Technologies for the Hydrogen Economy*. This roadmap will be used to guide R&D on critical manufacturing technologies and technical standards required for high-volume production, and to direct future public-private partnerships that will facilitate transfer of technology to industry through cost-shared projects.

Purpose of This Document

This document on manufacturing R&D for systems that produce and distribute hydrogen is one of three documents that have been prepared for the Workshop on Manufacturing R&D for the Hydrogen Economy. The other two documents cover manufacturing R&D for systems that store hydrogen and for proton exchange membrane fuel cells.

This material is intended to provide information to workshop participants for their use prior to and during the workshop. This paper was written by the DOE roadmap team and NIST in consultation with industry participants.

The paper covers the following topics that will be addressed in the workshop:

- What hydrogen system components need to be manufactured to begin the transition from petroleum to hydrogen between now and 2025?
- What is the state of manufacturing technologies for these components and systems?

In addition, the workshop will identify and prioritize topics for public-private R&D on manufacturing systems to produce and distribute hydrogen.

Hydrogen Production and Delivery

In the near-term, distributed production of hydrogen—via reforming of natural gas or bio-derived liquid fuels and via small-scale water electrolysis—appears to be the most viable approach for introducing hydrogen and beginning to build a hydrogen infrastructure. In the longer term, large centralized hydrogen production facilities, based on hydrogen production via coal gasification with sequestration and possibly via biomass gasification, that can take advantage of economies of scale, will be needed to meet increased hydrogen demand. Because the workshop is focusing on manufacturing R&D for the near-term, centralized hydrogen production facilities will not be considered in the workshop.

Today, production of hydrogen is capital intensive, and the contribution of capital to the cost of hydrogen is larger for smaller hydrogen production facilities designed for distributed applications. The capital contribution to the cost of hydrogen is 21% for a large 330,000 kg/day plant, and it rises to 52% for a 3,800 kg/day facility[1] (approximates a hydrogen gas station serving 300 vehicles per day[2]).

The larger contribution of capital to the cost of hydrogen for the smaller hydrogen production facility is the result of site-specific fabrication of fuel processing systems, which include

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[1] "Direct Hydrogen Fueled Proton Exchange Membrane Fuel Cell System for Transportation Applications," Hydrogen Infrastructure Report, Contract No DE-!C02-94CD50389
[2] Basis: 15 gallons per fill up. 0.9 kg hydrogen is a gallon of gasoline energy equivalent.

reformers, shift catalyst beds, and pressure swing adsorption clean up subsystems. Standardization of design has not been established for hydrogen production facilities. In turn, design for manufacture has not been applied to standardization of the subsystems. Producing reformers and hydrogen purification systems based on site-specific requirements does not afford manufacturing cost reductions associated with volume.

The cost of safe and efficient hydrogen production and delivery technologies must be lowered enough to be competitive with gasoline, without adverse environmental impacts. Today the cost of high-volume hydrogen production and delivery is three to four times the DOE target of $1.50-2.00/gge untaxed (gge is gasoline gallon equivalent on an energy basis). This reduction in cost may come both from revolutionary advances in production technologies as well as in reductions in the cost of manufacturing the new systems.

Distributed Reforming

While hydrogen production in large facilities is a highly developed industry that is continuing to advance, distributed hydrogen generation is not so well developed. In the absence of large scale delivery networks, distributed generation is a key pathway to a hydrogen infrastructure. The goal of advanced manufacturing is to reduce the capital cost of the fuel processor while boosting efficiency. Both can be realized through a fundamental effort to simplify and thermally integrate the hydrogen production process (Figure 1). The DOE technical targets for hydrogen production from gaseous and liquid fuels are listed in Attachment A.
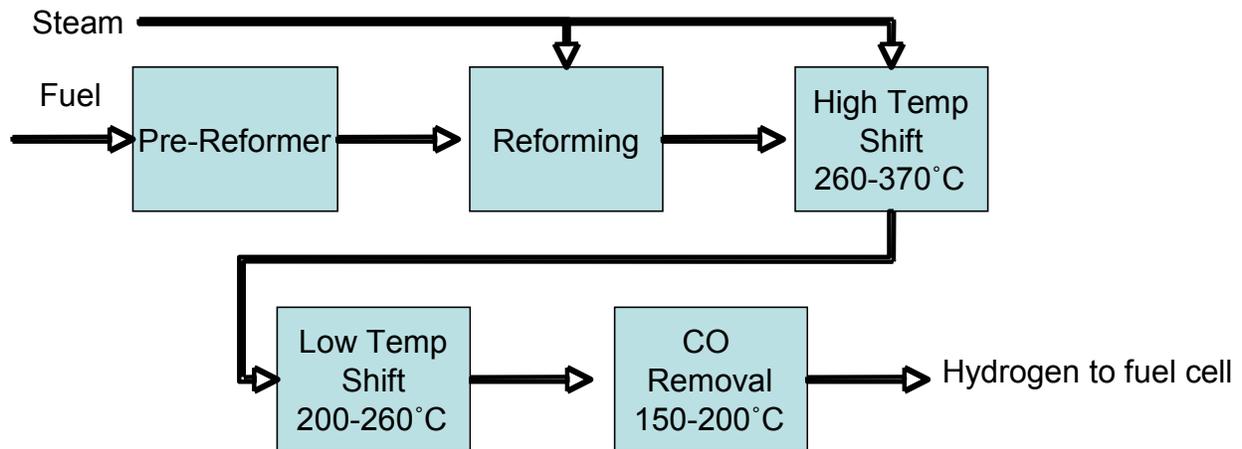
Figure 1. Schematic Representation of the Stages in Simple Steam or Autothermal Reformer. The pre-reforming step is where inorganic sulfur is converted to H_2S, via hydrogenation and then removed from the gas stream. The reforming step can be steam, autothermal, or partial oxidation where the hydrocarbon fuel is converted to a synthetic fuel (H_2 and CO). In the high and low temperature shift stages, CO is oxidized to CO_2 by a catalytic process with steam. The final CO removal or polishing step is typically accomplished using a catalytic oxidation of the remaining CO to CO_2.

The key components of the reforming system are the reformer, shift reactors, carbon monoxide (CO) polisher, and desulfurization stage. All of the reforming, shift, and desulfurization processes depend on a catalyst to promote the reaction in question. Cost drivers for the catalyst layer are materials (precious metal) costs, process cost to apply the catalyst to the support, and process cost to produce the support itself. In the case of a supported catalyst, the catalyst is typically applied to a carbon by wet chemistry method, often using salts of the catalytic metal. Needs include:

- Alternative, high through-put methods to prepare supported catalyst would decrease the cost of supported catalyst manufacture.
- Deposition methods, such as vapor deposition, physical deposition, and semiconductor processing technology, offer alternative manufacturing approaches that could drive down cost.
- High-throughput processes for producing uniform, high-strength supports such as extrusion need to be evaluated.
- Concepts such as "just in time production and lean manufacturing" processes, and approaches such as Six Sigma / Total Quality Management should be applied to the manufacture, fabrication, and assembly of hydrogen production facilities to drive down the capital cost.

Integrated Systems

The conventional approach requires reformer effluent cooling and H_2S scrubbing, followed by shift, and CO removal (Figure 1). These processes, along with steam generation and tail gas combustion, can be readily integrated into a single, all brazed/welded construction. Next

generation concepts may include an integrated membrane separation device. Approaches to system integration may include:

- Design and manufacturing concepts for integrating hydrogen membrane separators within a small shift converter in reformer itself.
- System designs for manufacturability and assembly could simplify the manufacturing process and drive down manufacturing costs.
- Integration of multiple components into a single reactor or system with fewer components will reduce overall costs.
- Rapid prototyping methods coupled with computer aided design (CAD) processes may provide ways to accelerate the development of low-cost manufacturing methods.

Thermal Management

Major components in the manufacture of the thermal management subsystem include the heat exchanger and associated pumps and coolant follow controllers. The thermal management system could be simplified by:

- Integrating these components into a subsystem and developing material joining methods and optimizing sealing systems could greatly enhance the manufacturability of the thermal management subsystem.
- Rapid prototyping methods coupled with CAD processes may provide a means to accelerate the development of low-cost manufacturing methods.
- Advancing the manufacturing of porous metal materials is a potential area of interest.

Water Management

Steam and autothermal reforming require water boilers, makeup water, and condensate recovery. A steam generator can be integrated into the fuel processor. Water recovery is always problematic, especially in the case of low-pressure systems, and is alleviated by using high pressure. High-temperature water recovery is an interesting area that can dramatically affect capital cost. Such systems use process heat to essentially raise the water recovery temperature. There are needs for

- Integrating these components into a subsystem and developing material joining methods and optimizing sealing systems could greatly enhance the manufacturability of the water management subsystem.
- Rapid prototyping methods coupled with CAD processes may provide a means to accelerate the development of low-cost manufacturing methods.

Joining

Joining of materials or components is one of the single largest contributors to the overall system cost. Conventional methods of joining (welding) materials are convective processes in which the microstructure of the weld is different from the microstructure of the bulk components. This may be due to the filler used to facilitate the weld or due to the convective mixing imparted by the high process temperatures used to promote the weld. Whatever the case, welding is a slow, costly process, requiring nondestructive analysis to ensure that the joins meet quality standards. Welds can become the critical flaw in systems where they come directly in contact with hydrogen

because in such cases they can become sites for enhanced hydrogen diffusion and embrittlement. There is a great need for:

- Advanced, rapid, low-cost methods for joining materials that minimize microstructural changes.
    - A solid-state joining process like friction stir welding is an example of an innovative emerging process that may impact future systems.
    - Electrochemical welding, "tube fuse," processes used for pipes are rapid and inexpensive and may increase throughput.

Heat Treatment/Annealing of Materials

Annealing materials at high temperature during production or fabrication is a timely process that greatly impacts the final cost of the product. There is vast interest in developing and implementing processes to reduce production time and costs in order to rapidly anneal and heat treat materials.

- One area of interest is rapid infrared processing[3]. The fundamental significance of this unique capability allows for never before achievable control of diffusion on the nanoscale over broad areas that cannot be accomplished with existing technologies. The broad area processing capability allows for homogeneous microstructural distribution and minimal residual stresses leading to potentially exceptionally uniform properties.
- Other unique processing capabilities of interest are high frequency microwave heating and fiber optic laser techniques. These technologies need to be critically assessed for targeted materials systems and needs in order to ascertain their relevance.

Hydrogen Separation

The current technology for large-scale industrial hydrogen production typically employs a two-step system for purifying hydrogen from the feed gas:

1. One or two water-gas-shift (WGS) reactors generate additional hydrogen from the CO in the gas mixture;
2. A pressure-swing adsorption (PSA) unit removes impurities such as CO, CO_2, CH_4, H_2O, and H_2S.

Depending on the hydrogen purity required, polishing filters may also be employed to remove specific trace impurities. Each of these steps adds capital and operating costs to the system and affects overall system efficiency. Integrating or replacing the WGS reactor(s) and/or PSA unit with advanced hydrogen integrated reaction and separation membrane modules may significantly reduce hydrogen production costs by reducing capital costs, lowering operating and maintenance (O&M) costs, and improving system efficiency.

Pressure-Swing Adsorption
PSA is an adiabatic process used to remove impurities from a hydrogen-rich feed gas at high pressure. Relative to membrane purification, PSA is thought to be the lower power, lower cost (at this time) option. The PSA produces the purified product with only a small drop in pressure relative to the feed, and regenerates by dropping the pressure to near atmospheric where it passes

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[3] High density infrared plasma arc processing equipment utilizes a unique technology to produce extremely high-power densities up to 20 kW/cm^2, which allows heating rates approaching 600,000°C/s over large areas (currently ~1,000 cm^2).

through a near-atmospheric pressure burner to recover the waste energy. Some of the typical adsorbents used are zeolitic molecular sieves, activated carbon, silica gel, and activated alumina. While relatively mature, PSA could benefit from:

- Large-scale production of uniform adsorbents,
- Low-cost manufacturing routes for the valving and pressure vessels,
- Advanced joining technology.

The manufacture of small modular systems with a single striated bed is of great interest for distributed production.

Membrane Technology for Hydrogen Separation
Both molecular and atomic transport membranes are at a stage where they can be considered as technologies to separate and purify hydrogen. The technical targets for membranes are listed in Attachment A. Membranes rely on dropping the hydrogen pressure to generate the purified product. While simpler in operation, they do not yet exhibit the reliability of PSA and have added compression costs.

Atomic transport membranes (also referred to as dense metallic membranes) transport hydrogen atoms that have dissolved into a dense metal matrix. These membranes are comprised of a thin, dense metallic layer (usually palladium or palladium alloys) supported on a porous layer. Upon coming into contact with the metal film, molecular hydrogen dissociates into atoms that then pass through the film and recombines into hydrogen molecules. The metal layer is typically formed from metal composites, thin palladium, or a palladium-alloy metal that is supported on an inexpensive, mechanically strong support. The most mature membrane option for hydrogen separation is palladium-silver alloy membranes. These membranes are prepared by vapor or gas phase deposition of Pd onto a porous metallic or ceramic support. Failures occur due to debonding with the support, chemical interaction between the support and membrane during operation, and non uniformities in the coating due to surface roughness of the support layer. The manufacturing needs include:

- Development of cost-effective membrane fabrication methods for economically producing defect free, thin film Pd membranes in a large-scale production model
  - Processes such as "RABiTS[4]", for example, or other novel fabrication processes developed for other applications may lead to breakthroughs.
- Development of fabrication methods for reproducible production of thin walled (light weight) supports with the proper pore size distribution and/or flatness.
- Advances in joining technology may be required for the pressure vessels encapsulating these membrane systems.

Molecular transport (microporous) membranes are essentially micro-filters. The pores of the membrane are sized to enable the very small hydrogen molecule (at 2.89Å) to move through the membrane while larger gas molecules are left behind. Selectivity is based not only on molecular size but also on how the molecule moves through the medium (mean free path) and on the viscosity of the gas stream. Permeation rate is affected by the pore size, thickness, tortuosity, and total porosity (pore volume) of the membrane and the system temperature and pressure. Molecular transport membranes have been made using sol-gel deposition of metallorganic

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[4] U. S. Patent 5,739,086 (1998).

precursors onto a porous metal or ceramic support or by a classified fabrication process developed by Oak Ridge National Laboratory. The main failure of this class of membrane is through non uniformities in the pore size distribution (i.e. large pores lead to cross over of unwanted gas species). The manufacturing needs for molecular membranes include:

- Fabrication methods for reproducible production of thin walled (light weight) supports with the uniform flatness,
- The development of cost-effective thin film processes that will yield sub-nanometer porous films for molecular transport,
- Advances in joining technology may be required for the pressure vessels encapsulating these membrane systems.

Hydrogen Compression

Current membrane separation devices use off-the-shelf compressors that are heavy, costly, inefficient, and not designed to work in conjunction with small modular membrane separation processes being developed.

- Designs for manufacturability, assembly, mass, volume, and cost reduction is a generic need.
- Explore novel compression technology (i.e., reversible metal hydride cycles).

Electrolyzer Systems

Two types of electrolyzer systems are available commercially: alkaline and protein exchange membrane (PEM). Both are composed of the following subsystems: (1) the cell stack, (2) the balance-of-plant, and (3) system controls. Technical targets are listed in Attachment A. Manufacturing issues with PEM electrolyzers are synergistic with the manufacturing issues in PEM fuel cells, and the background document on PEM fuel cell manufacturing should be reviewed to understand the existing needs.

Cell Stack

Alkaline systems are similar to PEM electrolyzers in that they have a membrane electrode assembly. The one difference is that they have a liquid, hydroxide-based electrolyte.

The membrane-electrode-assembly is a three-layer structure attached to a nickel current collector sandwiched around either a flowing or an immobilized electrolyte. The catalyst layers adjacent to each side of the electrolyte are transition or noble metal supported on carbon. The thickness of the catalyst layer can approach 25–50 μm but would, on average, be thinner. The gas diffusion layers, making up the outer two layers adjacent to a catalyst layer, are porous PTFE (Teflon) about 200–400 μm thick. These layers are typically manufactured using calendering technology.

Catalyst and Catalyst Layers

Cost drivers for the catalyst layer are materials (precious metal) costs, process cost to apply the catalyst to the carbon support, and process cost to apply the carbon supported catalyst to the current collector. For the processing of supported catalyst, the catalyst is typically applied to carbon by wet chemistry or physical methods such as co-precipitation or ball milling.

- Deposition methods, such as vapor deposition, physical deposition, and semiconductor processing technology, offer alternative manufacturing approaches that could drive down cost.

Bipolar Plates

Most alkaline systems are monopolar—that is, they do not require a bipolar plate. However, Gibbs Energy has recently been developing electrolyzers that will require a bipolar plate. Graphite would be the most suitable near-term choice for a bipolar plate.

The ability to manufacture plates without post-machining or grinding to assure flatness and parallelism is a critical need. A 25-μm increase in thickness for a bipolar plate, when repeated in a cell stack, could result in a 10-cm tilt in an 80-kW stack (approximately 400 cells). Building a cell stack with such a repeatable variation would obviously not be feasible; however, this hypothetical example illustrates the critical importance of tolerance control. Lack of tolerance control in the manufacture of the flowfields can result in uneven distributions of the reactants. Performance, durability, and the life of the fuel cell will all be impacted by the uneven distribution of the reactants. Precise control of the dimensions of the flow fields is critical for the manufacture of bipolar plates.

- Injection molding of carbon and graphite materials has been proposed as a high-rate method of forming graphitic bipolar plates.
- Research and development on alternative plate fabrication is critical for establishing methods that can maintain the exacting dimensions and physical properties of bipolar plates.

Frames and Manifolds

External manifolds are made from commercial-grade plastics using injection molding. In some cases the MEA is integrated into the injection molding process, producing a monolithic piece containing the MEA and manifolds in a single piece that can be easily stacked. Once the MEAs are produced, they are attached to the stack frame, in some cases by injection molding. This produces a gas-tight connection. However, injection molding is a fast, capital-intensive process.

- New processes to integrate the MEA into a polymer frame are needed. Integration of the sealing process with the manufacturing of reactant manifolds is an obvious, but possibly difficult manufacturing method to develop.

Cell Stack Assembly and Sealing

With the integration of the MEA into the frame assembly, one possible route for stacking and sealing stacks is through the use of friction welding. Leak-tight seals require good stack design and wide seal areas to accommodate the sliding of the frame during welding. Stacks are built one-half cell at time; only 100 elements (stacked) are possible due to equipment limitations. In stacks requiring a bipolar plate, sealing will require the use of a high-speed sealing process. For example, Hydrogenics injects the sealant under pressure during the assembly process. The stack itself serves as the injection mold.

- Designs for manufacturing and assembly may provide pathways to high-rate construction of rugged fuel cell stack systems

Gaseous Delivery of Hydrogen

Hydrogen delivery by pipelines is currently the lowest cost option at high volumes. The DOE technical targets are listed in Attachment A. To enable delivery of pressurized gaseous hydrogen in pipelines will require advancements in joining, materials heat treatments, compressor

development, and potentially coatings technologies. All of these except coatings have been discussed, previously. Other needs include:

- Production of long lengths of seamless pipes
- In-situ deposition and annealing of coatings using robotic processes
- Development of non evasive inspection PIGs that do not induce surface flaws during use.

Cross-Cutting Synergies between Hydrogen Production and Fuel Cells

The main area where significant cross over exists is between fuel cells and electrolyzers based on PEM technology. In addition, alkaline electrolyzers would benefit greatly from the balance of plant developments discussed in the PEM fuel cell document. The following list indicates the areas where there are synergistic needs for advancements in manufacturing for both fuel cells and hydrogen production and delivery.

- thermal management
- joining
- heat treatment of materials
- compressor technology

Cross Cutting Issues

(prepared by NIST)

As outlined in the previous section, manufacturing for the hydrogen economy covers a large spectrum of manufacturing technologies, from continuous chemical processes to discrete mechanical fabrication processes. As such, there are diverse issues and challenges associated with each of these manufacturing technologies. However, there are significant mutual influences among these technologies to affect the overall feasibility of the hydrogen economy. For example, while some continuous chemical process technologies rely on advances in discrete mechanical fabrication for cost reductions (e.g. fuel injectors used in gasifiers, feed systems) other discrete manufacturing technologies benefit from advances in continuous processes (e.g. gas purity, water management). Thus, the working group is able to identify a small set of challenges that are applicable to most of the manufacturing technologies. This section provides a preliminary summary of these cross cutting issues.

Metrology and Standards

Metrology provides quantitative information about a manufacturing process and its output. Thus it is key to understanding and improving any manufacturing technology. The ability to reliably measure various process parameters and other critical manufacturing process outputs enables cost effective manufacturing. Specific metrology needs of manufacturing for the hydrogen economy include the areas of dimension and form of components, micro structures and surfaces, particle size and distribution, thin and thick film coatings, pressure, temperature, vacuum, gas flow, water transport, resistance, conductivity, and electrical power.

Related issues include the need for standard measurement methods and protocols for these properties. Such standards ensure quality in the supply chain, lower costs, enhance international trade, and improve the quality of the end products.

Modeling and Simulation

Modeling and simulation can significantly advance the development and optimization of manufacturing processes, and thus are key elements in the development of a viable manufacturing for hydrogen economy.

Knowledge Bases

To support modeling efforts, there is a need for information and knowledge about new materials and sealants, including their processibility, formability, machinability, and compatibility with other materials and gases. There is also a need for new process technologies, fundamental correlations between manufacturing parameters, and performance parameters. Creating pre-competitive, easily accessible, user-friendly knowledge bases for the use of the hydrogen industry will foster further innovation in this area.

Design for Manufacturing and Assembly

In order to cost effectively move from existing small-batch production to high-volume production, design-for-manufacturing (DFM) methodologies have to be used at the earliest stages of product development. DFM principles that should be considered include component selection for reduced parts counts designs that can be produced consistently at both low and high volumes, and realistic tolerance analysis and specifications.

Sensing and Process Control

Sensors and process control technologies are key enablers for increasing the reliability and quality of manufacturing processes while reducing cost. Low cost sensing and sensor fusion technologies with reliable sensor networks are therefore needed for in-process sensing of processes and in-operation sensing of product performance.

State of Manufacturing

Centralized hydrogen production facilities have been produced for many years and are designed and constructed based on the quantity of hydrogen to be delivered. As such there is no mass customization or commercialization of most of the system components except for heat exchangers, catalysts, and gas clean up technology (i.e. PSA) which have widespread application in other industries. Distributed generation systems and their respective components are in the early stages of manufacturing and for the most part are constructed as needed for a specific design level of hydrogen production.

Attachment A

Technical Targets from "Multi-Year Research, Development and Demonstration Plan: Planned Program Activities for 2003-2010", U.S. Department of Energy Hydrogen, Fuel Cells and Infrastructure Technologies Program, February 2005.

Table 3.1.2. Technical Targets: Distributed Production of Hydrogen from Natural Gas				
Characteristics	**Units**	**Calendar Year**		
		2003 Status	**2005 Target**	***Proposed* 2010 Target**
Total Energy Efficiency$_e$	%(LHV)	65.0	65.0	75.0
Production Energy Efficiency	%(LHV)	69.0	69.0	80.0
Storage, Compression, and Dispensing Energy Efficiency$_f$	%(LHV)	94.0	94.0	94.0
Total Hydrogen Cost	$/gge H_2	5.00	3.00	2.50
Detailed Cost Breakdown − These calculations are for guidance only and not necessarily the research targets to achieve the total energy efficiency and cost goals.				
Capital Cost Contribution	$/gge H_2	2.70	1.40	0.89
Production	$/gge H_2	1.90	0.60	0.30
Storage, Compression, Dispensing$_f$	$/gge H_2	0.80	0.80	0.59
Fixed O&M Cost Contribution	$/gge H_2	1.20	0.60	0.45
Feedstock Cost Contribution	$/gge H_2	0.90	0.80	0.92
Other Variable O&M Cost Contribution	$/gge H_2	0.20	0.20	0.24

Table 3.1.3. Technical Targets: Distributed Production of Hydrogen from Bio-Derived Renewable Liquids [a,b]

Characteristics	Units	Calendar Year			
		2003[c] Status	2005[c] Target	2010[c] Target	2015[d] Target
Total Energy Efficiency[e]	%	46.0	46.0	66.0	70.0
Production Energy Efficiency	%	49.0	49.0	70.0	
Storage, Compression, Dispensing Energy Efficiency[f]	%	94.0	94.0	94.0	
Total Hydrogen Cost	$/gge	6.70	5.90	3.60	2.50
Detailed Cost Breakdown – These calculations are for guidance only and not necessarily the research targets to achieve the total energy efficiency and cost goals.					
Capital Cost Contribution	$/gge	1.90	1.30	0.90	
Production	$/gge	1.10	0.50	0.50	
Storage, Compression, Dispensing[f]	$/gge	0.80	0.80	0.40	
Fixed O&M Cost Contribution	$/gge	0.70	0.50	0.40	
Feedstock Cost Contribution[g]	$/gge	3.80	3.80	1.80	
Other Variable O&M Cost Contribution	$/gge	0.30	0.30	0.50	

[a] Economic parameters used were 20 yr. analysis period, 10% IRR after taxes, 100% equity financing, 1.9% inflation, 38.9% total tax rate, MACRS 7-year depreciation, 70% capacity factor. 2000$ calculations were inflated by 6% to yield 2003$.

[b] The electricity price was set at $.07/kWhr in 2000$ based on the levelized price between 2005-2025 based on the EIA AEO 2004 for commercial rates.

[c] The 2003 status, 2005, and 2010 target are based on an initial analysis of distributed reforming of ethanol at a design capacity of 1500 kg/day of hydrogen based on available information.

[d] The 2015 target is based on what might be achievable with breakthroughs in technology and alternative bio-derived renewable liquids.

[e] Energy efficiency is defined as the energy of the hydrogen out of the process (LHV) divided by the sum of the energy into the process from the feedstock (LHV) and all other energy needed. The electrical energy utilized does not include the efficiency losses from the production of the electricity.

[f] Storage capacity for 1100 kg of hydrogen at the forecourt is included. It is assumed that the required hydrogen pressure for refueling is 5000 psi for 2003 and 2005. It is assumed that in 2015, the pressure for hydrogen refueling is 1500 psi.

[g] For 2003 and 2005 the price of ethanol used is $1.15/gallon in 2003$. This is a typical price for ethanol in the fuel market over the past 5 years. For 2010, the price of ethanol used is $.85/gallon in 2003$. It is assumed that this cost reduction is possible based on using less purified and wet ethanol (i.e. only using a single distillation step rather than two distillation steps and molecular sieve drying currently used in ethanol manufacture from corn), further improvements in ethanol production from corn and/or the introduction of other lower cost ethanol production technology such as from cellulosic biomass.

Table 3.1.5. Technical Targets: Dense Metallic Membranes for Hydrogen Separation and Purification

Performance Criteria[a]	Units	Calendar Year			
		2003 Status[b]	2005 Target	2010 Target	2015 Target
Flux Rate[c]	scfh/ft²	60	100	200	300
Membrane Material and All Module Costs[d]	$/ft² of membrane	2,000	1,600	1,000	<500
Durability[e]	hr	<8,760[f]	8,760	26,280	>43,800
ΔP Operating Capability[g]	psi	100	200	400	400-1,000
Hydrogen Recovery	% of total gas	60	>70	>80	>90
Hydrogen Quality[h]	% of total (dry) gas	>99.9	>99.9	>99.95	99.99

[a] The membranes must be tolerant to impurities. This will be application specific. Common impurities include sulfur and carbon monoxide.
[b] Based on membrane shift reactor with syngas.
[c] Flux at 20 psi hydrogen partial pressure differential with a minimum permeate side total pressure of 15 psi, preferably >50 psi and 400 °C.
[d] The membrane support structure is approximately three times membrane material costs.
[e] Intervals between membrane replacement.
[f] Hydrogen membranes have not been demonstrated to date, only laboratory tested.
[g] Delta P operating capability is application dependent. There are many applications that may only require 400 psi or less. For coal gasification 1000 psi is the target.
[h] Based on current available PEM fuel cell information, the tentative contaminant targets are: <10ppb sulfur, <1 ppm carbon monoxide, <100 ppm carbon dioxide, < 1 ppm ammonia, < 100 ppm non-methane hydrocarbons on a C-1 basis, oxygen, nitrogen and argon can not exceed 2% in total, particulate levels must meet ISO standard 14787.

Notes: Revised targets take into consideration input received at the September, 2004 H₂ Separations Workshop. These targets are undergoing detailed engineering analysis. Membrane systems should be demonstrated within a temperature range between 250-1,000 degrees Celsius. Also, parasitic power requirements (that used to recompress the hydrogen downstream of the membrane due to potential pressure drops across the membrane) should be minimized.

Table 3.1.6 Technical Targets: Microporous Membranes for Hydrogen Separation and Purification

Performance Criteria[a]	Units	2003 Status	2005 Target	2010 Target	2015 Target
Flux Rate[b]	scfh/ft²	100	100	200	300
Membrane Material and All Module Costs[c]	$/ft² of Membrane	450-600	400	200	<100
Durability[d]	hr	<8,760[e]	8,760	26,280	>43,800
ΔP Operating Capability[f]	psi	100	200	400	400-1000
Hydrogen Recovery	% of total gas	60	>70	>80	>90
Hydrogen Quality[g]	% of total (dry) gas	≥90	95	99.5	99.99

[a] The membranes must be tolerant to impurities. This will be application specific. Common impurities include sulfur and carbon monoxide.
[b] Flux at 20 psi hydrogen partial pressure differential with a minimum permeate side total pressure of 15 psi, preferably >50 psi and 400 °C.
[c] The membrane support structure cost is approximately three times more than membrane material costs.
[d] Intervals between membrane replacement.
[e] Hydrogen membranes have not been demonstrated to date, only laboratory tested.
[f] Delta P operating capability is application dependent. There are many applications that may only require 400 psi or less. For coal gasification 1000 psi is the target.
[g] Based on current available PEM fuel cell information, the tentative contaminant targets are: <10ppb sulfur, <1 ppm carbon monoxide, <100 ppm carbon dioxide, < 1 ppm ammonia, < 100 ppm non-methane hydrocarbons on a C-1 basis, oxygen, nitrogen and argon can not exceed 2% in total, particulate levels must meet ISO standard 14787.

Note: Revised targets take into consideration input received at the September, 2004 H₂ Separations Workshop. These targets are undergoing detailed engineering analysis. Membrane systems should be demonstrated within a temperature range between 250-1,000 Degrees Celsius. Also, parasitic power requirements (that used to recompress the hydrogen downstream of the membrane due to potential pressure drops across the membrane) should be minimized.

Table 3.1.4. Technical Targets: Water Electrolysis[a]

Characteristics		Units	1500 kg/day refueling station			Central Renewable[b]
			2003 Status	2005 Target	2010 Target	2015 Target
Power Conversion, Cell Stack, Balance of Plant[c]	Cost	$/gge H₂	0.95	0.80	0.39	0.24
	Total Cell Efficiency	%	66	68	76	77
Compression, Storage, Dispensing[d]	Cost	$/gge H₂	0.83	0.77	0.19	0.08
	Efficiency	%	94	94	99	99.5
Electricity[e]	Cost	$/gge H₂	2.57	2.47	1.89	1.32
O&M	Cost	$/gge H₂	0.80	0.71	0.38	0.11
Total[f]	Cost	$/gge H₂	5.15	4.75	2.85	2.75[g]
	Efficiency	%	62	64	75	76

[a] Economic parameters used were: 20 yr. analysis period, 10% IRR after taxes, 100% equity financing, 1.9% inflation, 38.9% total tax rate, MACRS 7-year depreciation, 70% capacity factor. The H2A results in 2000$ were inflated by 6% to yield 2003$.

[b] Renewable Option: Calculation base on delivering 50,000 gge hydrogen per day (1000+ gge modules) with option of electricity co-production. Electricity back up provided by grid.

[c] Includes power conversion, cell stack and balance of plant (efficiency based on AC electric input to hydrogen output on a LHV basis).

[d] Compression improvements result from integral electrochemical or other system compression to reduce or eliminate mechanical compression. Lower pressure storage assumed in 2015.

[e] Electricity at EIA projected industrial electricity rate for 2003-2005. $.04 per kWh assumed in 2010 based on regional industrial electricity rate and new renewable technologies on the grid. $.03 per kWh assumed in 2015 with central wind and grid back up. $.03 per kWh also corresponds to the Office of Wind and Hydropower 2012 production cost goal for class 4 wind resources.

[f] Based on system capital cost per kWe of $700, $600 and $250 for the refueling station in 2003, 2005 and 2010, respectively, and $200 for the central station in 2015. Assumes high volume annual production (1,000 units for all purposes and all markets) of electrolyzer units in 2010-2015 and centralized facility benefiting from scale on installation.

[g] Includes $1.00 per gge delivery charge (transportation to the station, hauling and dispensing).

Table 3.2.2 Hydrogen Delivery Targets[a]

Category	2003 Status	2005	2010	2015
Pipelines: Transmission				
Total Capital Cost ($M/mile)[b]	$1.20	$1.20	$1.00	$0.80
Pipelines: Distribution				
Total Capital Cost ($M/mile)[b]	$0.30	$0.30	$0.25	$0.20
Pipelines: Transmission and Distribution				
Reliability (relative to H_2 embrittlement concerns and integrity)[c]	Undefined	Undefined	Understood	High (Metrics TBD)
H_2 Leakage[d]	Undefined	Undefined	<2%	<0.5%
Compression: Transmission				
Reliability[e]	92%	92%	95%	>99%
Hydrogen Energy Efficiency (%)[f]	99%	99%	99%	99%
Capital Cost ($M/compressor)[g]	$18	$18	$15	$12
Compression: At Refueling Sites				
Reliability[e]	Unknown	Unknown	90%	99%
Hydrogen Energy Efficiency (%)[f]	94%	94%	95%	96%
Contamination[h]	Varies by Design	Varies by Design	Reduced	None
Cost Contribution ($/gge of H_2)[i,j]	$0.60	$0.60	$0.40	$0.25
Liquefaction				
Small-Scale (30,000 kg H_2/day) Cost Contribution ($/gge of H_2)[k]	$1.80	$1.80	$1.60	$1.50
Large-Scale (300,000 kg H_2/day) Cost Contribution ($/gge of H_2)[k]	$0.75	$0.75	$0.65	$0.55
Small-Scale (30,000 kg H_2/day) Electrical Energy Efficiency (%)[k,l]	25%	25%	30%	35%
Large-Scale (300,000 kg H_2/day) Electrical Energy Efficiency (%)[k,l]	40%	40%	45%	50%
Carriers				
H_2 Content (% by weight)[m]	3%	3%	6.6%	13.2%
H_2 Content (kg H_2/liter)	Undefined	Undefined	0.013	0.027
H_2 Energy Efficiency (From the point of H_2 production through dispensing at the refueling site)[f]	Undefined	Undefined	70%	85%
Total Cost Contribution (From the point of H_2 Production through dispensing at the reueling site) ($/gge of H_2)	Undefined	Undefined	$1.70	$1.00
Storage				
Refueling Site Storage Cost Contribution ($/gge of H_2)[i,n]	$0.70	$0.70	$0.30	$0.20
Geologic Storage	Feasibility Unknown	Feasibility Unknown	Verify Feasibility for H2	Capital and operating cost <1.5X that for natural gas on a per kg basis
Hydrogen Quality[o]	>98% (dry basis)			

* All dollar values are in 2003 U.S. dollars

b The 2003 status is based on data from True, W.R., "Special Report: Pipeline Economics," Oil and Gas Journal, Sept. 16, 2002, pp 52-57. This article reports data on the cost of natural gas pipelines as a function of pipe diameter. It breaks the costs down by materials, labor, misc. and right of way. It is based on a U.S. average cost. A 15 inch pipe diameter was used for transmission and 2.5 inch for distribution. It was assumed that hydrogen pipelines will cost 30% more than natural gas pipelines based on advice from energy and industrial gas companies and organizations. The targeted cost reductions for 2010 and 2015 assume the right of way costs do not change.

c Pipeline reliability used here refers to maintaining integrity of the pipeline relative to potential hydrogen embrittlement or other issues causing cracks or failures. The 2015 target is intended to be at least equivalent to that of today's natural gas pipeline infrastructure.

d Hydrogen leakage based on the hydrogen that permeates or leaks from the pipeline as a percent of the amount of hydrogen put through the pipeline. The 2015 target is based on being equivalent to today's natural gas pipeline infrastructure based on the article: David A. Kirchgessner, et al, "Estimate of Methane Emissions from the U.S. Natural Gas Industry", *Chemosphere*, Vol.35, No 6, pp1365-1390, 1997.

e Compression reliability is defined as the percent of time that the compressor can be reliably counted on as being fully operational. The 2003 value for transmission compressors is based on information from energy companies that use these types and sizes of compressors on hydrogen in their own operations.

f Hydrogen energy efficiency is defined as the hydrogen energy (LHV) out divided by the sum of the hydrogen energy in (LHV) plus all other energy needed for the operation of the process.

g The 2003 value is based on data from "Special Report: Pipeline Economics," Oil and Gas Journal, Sept. 4, 2000, p 78. The compressor capital cost data was plotted vs. the power required for the compressor using the natural gas transmission compressor data provided. The capital cost was increased by 30% as an assumption for higher costs for hydrogen compressors. The power required was calculated assuming 1,000,000 kg/day of hydrogen flow with an inlet pressure of 700 psi and an outlet pressure of 1,000 psi.

h Some gas compressor designs require oil lubrication that results in some oil contamination of the gas compressed. Due to the stringent hydrogen purity specifications for PEM fuel cells, the 2015 target is to ensure no possibility of lubricant contamination of the hydrogen from the compression needed at refueling stations or stationary power sites since this compression is just prior to use on a vehicle or stationary power fuel cell.

i The 2003 value is based on utilizing the H2A Forecourt (refueling station) Model spreadsheet tool for a 1500 kg/day distributed natural gas hydrogen production case (www.eere.energy.gov/hydrogenandfuelcells). The standard H2A financial input assumptions were used. It was assumed that two compressors would be needed due to the currently unknown reliability of forecourt compressors, at a total installed capital cost of $600K. The electricity required assumed an isentropic energy efficiency of 70% and an electricity price of $.07/kWhr. The compression operation was assumed to have a fractional share of the forecourt fixed costs based proportional to its capital and the total capital cost of the forecourt.

j For 2003 and 2005, it is assumed that the hydrogen delivery pressure to the vehicle is 5000 psi. For 2010 and 2015, it is assumed that the hydrogen delivery pressure to the vehicle is 1500 psi or less based on the on-board vehicle storage program (Section 3.3) being successful in meeting its targets.

k The 2003 cost contribution and electrical energy efficiency was determined using the H2A Delivery Component Model spreadsheet using standard H2A financial input assumptions and the liquefaction spreadsheet tab (www.eere.energy.doe/hydrogenandfuelcells). The H2A spreadsheet information is based on data from other references cited in the H2A Delivery Component Model. References and a plot of liquefier capital cost as a function of capacity and a plot of actual energy used as a function of liquefier capacity are provided in the H2A Delivery Component model.

l Electrical energy efficiency is defined as the theoretical energy needed to liquefy the hydrogen divided by the energy actually needed in a hydrogen liquefaction plant. The theoretical energy is that energy needed to cool the gas to the liquefaction temperature and the energy needed for the ortho/para transition. The H2A Delivery Component Model (www.eere.energy.doe/hydrogenandfuelcells) provides the references and a plot of actual energy needed for current hydrogen liquefiers as a function of capacity.

m The 2010 hydrogen content targets are based on transporting 1500 kg of hydrogen in a truck. Although regulations vary to some degree by state, a typical truck is limited to carrying 25,000 kg of load and/or 113,000 liters of volume. The minimum hydrogen content (% by weight and kg H₂/liter) to achieve 1500 kg of hydrogen on the truck is determined by the maximum loads allowable. Trucking costs with this hydrogen payload are such that this transport option would seem attractive relative to the delivery cost objectives. A typical refueling station of 1500 kg/day of hydrogen servicing hydrogen fuel cell vehicles would service the same number of vehicles as typical gasoline stations serve today. This delivery option would require one truck delivery per day which is also typical of today's gasoline stations. The 2015 targets are calculated in the same way but assuming 3000 kg per truck load so that the one truck could service two refueling stations. The total cost and attractiveness of this delivery option would depend on the cost of the total carrier delivery system including the cost of discharging the hydrogen at the refueling station and any carrier regeneration costs.

n The 2003 value is based on utilizing the H2A Forecourt (refueling station) Model spreadsheet tool for a 1500 kg/day distributed natural gas case (www.eere.energy.gov/hydrogenandfuelcells). The standard H2A financial input assumptions were used. It was assumed that the hydrogen storage installed capital cost is $1.1M based on current technology and 1,100 kg of hydrogen storage. The storage operation was assumed to have a fractional share of the forecourt fixed costs based proportional to its capital and the total capital cost of the forecourt.

o Based on current available PEM fuel cell information, the tentative contaminant targets are: <10ppb sulfur, <1 ppm carbon monoxide, <100 ppm carbon dioxide, < 1 ppm ammonia, < 100 ppm non-methane hydrocarbons on a C-1 basis, oxygen, nitrogen and argon can not exceed 2% in total, particulate levels must meet ISO standard 14787. Future information on contaminant limits for on-board storage may add additional constraints.