FUEL CELL SUMMIT

A quarterly newsletter from the U.S. Department of Energy to supply information on U.S. regulation of fuel cells and hydrogen.

Publications on Efficiently Constructing Hydrogen Fueling Stations Available Soon

Courtesy of Russell Hewett, National Renewable Energy Laboratory

In a country of 200 million gasoline or diesel vehicles and 200 million fueling stations, fewer than 10 commercial-scale hydrogen fueling stations are currently in existence. As automakers begin to market fuel cell-powered cars, the Nation may need tens of thousands of hydrogen fueling stations to support these vehicles. The U.S. Department of Energy (DOE), through its National Renewable Energy Laboratory (NREL), and the National Fire Protection Association (NFPA) are working together to make hydrogen fueling stations for fuel cell-powered vehicles a reality.

The objective of the DOE/NFPA/NREL collaborative project is to help expedite the infrastructure for hydrogen-powered vehicles; specifically, to provide tools and step-by-step procedures that allow permitting officials to cost-effectively and efficiently permit hydrogen fueling stations. To support this effort, the project is developing a handbook and guidebook that will define requirements for typical hydrogen fueling stations and reference existing hydrogen-related codes and standards:

1. ***Handbook of a Sample of Successfully Operating Hydrogen Fueling Station Projects***
   - describes and provides engineering descriptions of five hydrogen fueling station projects
   - describes the hydrogen fueling process at each project
   - documents at least some of the codes and standards used to design and permit each project.
2. ***How to Permit a Hydrogen Fueling Station Guidebook for Building Code and Fire Safety Officials***
   - presents a generic hydrogen fueling station, based on the projects documented in the handbook
   - lists the applicable requirements for the different fueling station components and gives explanations about their functions
   - provides step-by-step permit review guidance for code officials
   - lists the current codes and standards that are applicable for each step.

Photograph of Ford's Hydrogen Fueling Station in Dearborn, Michigan.

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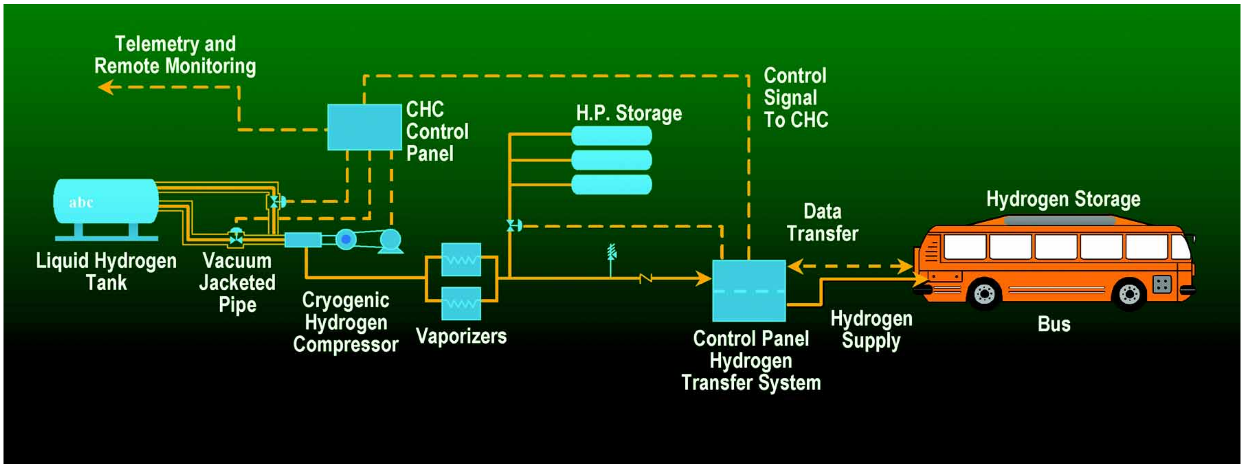

Schematic of the Chicago Transit Authority's Hydrogen Storage and Dispensing Facility

For additional information, contact:

Neil P. Rossmeissl at the U.S. Department of Energy
phone: (202) 586-8668
email: neil.rossmeissl@ee.doe.gov

or contact:

David L. Smith Pacific Northwest National Laboratory
phone: (509) 372-4553
fax: (509) 372-4370
To subscribe to this newsletter, send an email to dlsmith@pnl.gov

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Visit the Fuel Cells website at: www.pnl.gov/fuelcells

Fueling the Fuel Cell: Hydrogen Storage Options

Courtesy of George J. Thomas, Consultant, Hydrogen Technologies

Fuel cells hold great promise as an alternative to conventional internal combustion (IC) engines in vehicles. An important issue that remains to be resolved, however, is onboard hydrogen storage. At ambient pressure and temperature, the energy content of hydrogen is a mere 1/3000 of that of gasoline. Storage systems that increase fuel density also result in additional weight and volume above that of the fuel alone, impacting overall vehicle performance. How then do we store sufficient hydrogen onboard to achieve performance comparable to gas-powered vehicles in terms of vehicle range, weight, and usable payload volume?

Hydrogen shares the requirement for greater-than-ambient storage density with other gaseous fuels such as natural gas and propane. However, some unique aspects associated with hydrogen affect storage system considerations. For example, although hydrogen can be stored as a liquid, similar to propane, its low boiling temperature (20 K at ambient pressure) requires effective cryogenic insulation methods. Hydrogen also requires greater densification than typically used with other fuels to meet onboard storage requirements. In addition to compression and liquefaction, hydrogen can be stored by chemical methods, offering a high-density storage alternative. Before discussing storage options, let us look at energy density requirements.

Energy Density

The total energy content of gasoline, 31 MJ per liter (lower heating value), is very high–1 gal of gasoline has approximately the energy equivalent of 1 kg of hydrogen. However, if only hydrogen content is considered, the hydrogen energy density in gasoline is about 13 kg per liter gasoline (the additional energy is due to oxidation of the carbon in the fuel). Indeed, all fuels in their liquid state have hydrogen energy densities in the range of 10 to 13 MJ per liter of fuel. Hydrides, which chemically bond hydrogen atoms in a solid matrix, typically have energy densities similar to the fuels (about 10 MJ per liter). Liquid hydrogen, on the other hand, has a somewhat lower energy density (8 MJ per liter at ambient pressure) due to the looser packing of hydrogen molecules in the liquid state.

The energy density range of 10 to 13 MJ per liter appears to be a limit imposed by the nature of chemical bonds. Automakers have identified target energy densities of 6 to 12 MJ per liter of storage device and 6 to 12 MJ per kg of storage device (5 to 10 wt.% H_2) to satisfy market-driven requirements. Developing effective storage systems for wide-scale acceptance of fuel cell vehicles will clearly be challenging.

Storage Options

High-pressure gas storage Nearly all hydrogen-fueled vehicles currently being demonstrated use high-pressure gas cylinders for onboard storage because they are lightweight, straightforward to apply, and commercially available. Suppliers include Quantum Technologies, Irvin, CA; Dynetek Industries, Ltd., Alberta, Canada; Structural Composites Industries, Inc., Pomona, CA.

The critical technology for high-pressure containment has been high-strength graphite fiber-wound composite materials using polymer liners to further reduce the weight of these tanks. This technology can achieve the weight targets of 5 to 10 wt.% H_2. In spite of these positive attributes, development efforts continue in this and other areas to improve volumetric performance. At 5000 psi, the energy density is only about 2.75 MJ per liter, well below the lower target level. At 10,000 psi, the density is still somewhat below the lower target but approaches current hydride bed designs. Tanks capable of operating at the higher pressure are currently under development.

Liquid hydrogen storage Liquid hydrogen storage currently provides the highest storage density per unit volume of any of the storage options in practical systems. It is also reasonably low in weight. Ample evidence exists that cryogenic systems can be safely used and refueled on a vehicle. BMW has fielded a small fleet of sedans using liquid hydrogen storage to fuel modified IC engines to demonstrate their technology and to acquire much-needed operational experience. An automated liquid hydrogen refueling station is currently undergoing evaluation tests in Germany.

Important issues that must be resolved for this storage method to be accepted are control of boil-off, which impacts both storage efficiency and safety, and the additional energy cost associated with liquefaction.

Solid-state storage The chemical reactivity of hydrogen provides several solid-state storage options. Hydrogen is packed closest in chemically bonded structures that can yield energy densities of 10 to 12 MJ per liter. With current state-of-the-art storage system designs, however, this density is further reduced by mechanical, thermal, or other engineering requirements. Nonetheless, this storage option provides the potential to achieve the highest energy densities of all storage technologies and has the added advantages of being inherently low pressure and not requiring cryogenic techniques.

Solid-state storage materials can be either reversible (that is, they can be refueled *in situ* onboard a vehicle) or nonreversible where a reprocessing pathway for the spent material must be provided. Chemical hydrides, particularly borohydrides, are currently being developed as nonreversible storage materials. They exhibit good energy densities, with

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Standards Committee Activity Updates

- **ICC Codes**. The expected publication date of the 2003 Code Editions is February 2003. The next ICC Code Development Cycle will be a new, 18-month cycle. March 24 is the deadline for Code Committee Applications and New Code Change Proposals. July 3 is the tentative publication date of "Proposed Changes to the I-Codes." Public hearings will be Sept. 5-14 in Nashville, TN. Changes approved will be published in August 2004 in the 2004 Supplement. Code change proposal forms are available at www.intlcode.org. Contact: Eric Stafford (SBCCI), (205) 591-1853, (205) 592-7001 (fax), estaffor@sbcci.org.

- **NFPA 5000, Building Construction and Safety Code**. To obtain NFPA 5000 (Building Construction and Safety Code), call (800) 344-3555 or visit www.nfpacatalog.org. Contact: Karen Stein (NFPA), (617) 984-7263, kstein@nfpa.org.

- **NFPA 55, Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks**. NFPA 50A and 50B are being consolidated into a revised edition of NFPA 55 (2003 Edition) that will include storage and utilization requirements for all gases and expand coverage from consumer sites to consumer and manufacturer sites. Contact: Carl Rivkin (NFPA), (617) 984-7418, crivkin@nfpa.org.

- **NFPA Hydrogen Coordinating Group**. NFPA has formed the group to coordinate the development of hydrogen requirements at NFPA. Work began with an early-January conference call and late-January meeting in Quincy, MA. The group includes members of NFPA, and representatives of DOE, NHA, and the hydrogen industry. Contact: Carl Rivkin (NFPA), (617) 984-7418, crivkin@nfpa.org.

- **ISO TC 197, Hydrogen Technologies**. Two new work item proposals have been approved and circulated–N238, Hydrogen Generators Using Fuel processing Technologies and N239, Transportable Gas Storage Devices - Hydrogen Absorbed in Reversible Metal Hydrides. Contact: Karen Miller (NHA), (202) 223-5547, kmiller@ttcorp.com.

- **IEC TC 105, Fuel Cell Technologies**. WG#3 - Stationary Fuel Cell Power Plants plans to meet in Miami, FL, in early February 2003 to expand a draft with detailed requirements from the construction portion of the proposed U.S. Stationary Fuel Cell Power System standard. The standard does not cover portable or propulsion fuel cell power systems. Contact: Steve Kazubski (CSA America), (216) 524-4990 ext. 8303, steve.kazubski@csa-america.org or steve.kazubski@csa-international.org.

- **ASME PTC 50, Performance Test Code on Fuel Cell Power Systems**. PTC 50 provides test procedures for performance characterization of all components of fuel cell power systems. It includes methods for evaluating system energy inputs and electrical and thermal outputs to determine fuel-to-electrical energy conversion efficiency and overall thermal effectiveness. Issued November 29, the code is available in hardcopy or .pdf format at 1-800-843-2763 or www.asme.org/catalog. Contact: Jack Karian (ASME), (212) 591-8552, karianj@asme.org.

- **ASME Hydrogen Infrastructure Coordination Meeting.** ASME hosted the January 2003 meeting on the state of technology and standards. The group agreed on critical standards development items, including hydrogen sensors and alarms, efficient and lightweight hydrogen transportation tubes, hydrogen embrittlement of materials and plumbing, and vehicle fueling station standards. The group will report on the meeting at the Fuel Cells Codes and Standards Summit VII on May 28-29. Contact: Tony Androsky (US Fuel Cell Council), (202) 293-5500 ext. 15, androsky@usfcc.com.

- **NFPA 853, Installation of Stationary Fuel Cell Power Plants**. The Report on Comments will be presented in May 2003 for adoption by the Standards Council. No other Technical Committee meetings are planned for CY2003. Contact: Don Drewry (Hartford Steam Boiler), Don_Drewry@hsb.com; or Carl Rivkin (NFPA), (617) 984-7418, crivkin@nfpa.org.

- **NFPA 70, National Electrical Code - Article 692, Fuel Cell Plant**. The Code Making Panel for Article 692 will meet January 16-18, 2003, in Hilton Head, SC, for action on proposals. Contact: Jean O'Connor (NFPA), (617) 984-7421, (617) 984-7070 (fax), joconnor@nfpa.org.

- **National Evaluation Service (NES)**. Consolidated as the International Code Council (ICC) on February 1, 2003. Contact: Darren Meyers (ICC), (800) 214-4321 ext. 307, or Dave Conover (ICC), (703) 931-4533. See: www.iccsafe.org.

- **IEEE P1547, Distributed Resources and Electric Power Systems Interconnection**. A draft P1547 addressing unresolved negative ballots is being recirculated to the ballot group. IEEE plans to approve and publish the draft in CY2003 as an ANSI/IEEE consensus standard. The P1547.1, .2, and .3 Working Groups (WG) met in October 2002 and January 2003 to begin drafts. The P1547 Series of Standards groups will meet again in June. Contact: Richard DeBlasio (NREL), (303) 275-4333, ddeblasi@tcplink.nrel.gov; or Tom Basso (NREL), (303) 275-3753, thomas_basso@nrel.gov.

- **UL1741, Standard for Inverters, Converters and Controllers for Use in Independent Power Systems**. Underwriters Laboratory (UL) distributed a second draft Second Edition of UL 1741 for public comment in November 2002. UL will develop and propose a third draft for another round of comments later in 2003. Contact: Tim Zgonena (UL), (847) 272-8800 ext. 43051, (847) 509-6298 (fax), timothy.p.zgonena@us.ul.com; or Susan Malohn (UL STP Secretary), (847) 664-1725, susan.p.malohn@us.ul.com.

2003

Calendar of Events

FEB

17-19	**8th Annual National Ethanol Conference: Policy & Marketing**. Camelback Inn Marriott Resort, Scottsdale, AZ. Contact: (800) 567-6411. See: www.ethanolrfa.org/nec.shtml.
18-20	**Global Alternative Fuels Forum**. Hilton Munich City Hotel, Munich, Germany. Contact: +44.124.252.9090, c.hodson@theenergyexchange.co.uk. See: www.theenergyexchange.co.uk.
19-21	**Clean Heavy Duty Vehicles: Creating the Road Map for Advanced Technologies and Fuels.** Tempe Mission Palms, Tempe, AZ. Contact: (626) 744-5600, sromeo@calstart.org. See: www.calstart.org.
19-22	**IDROGENO & FUEL CELLS 2003**. Milan, Italy. Contact: +39.02.66.30.17.45, mireille.terond@idrogenoexpo.com. See: www.idrogenoexpo.com.
20-23	**India International Clean Energy Expo 2003**. Bangalore, India. See: www.cleanenergyexpo.com.
23-26	**Advances in Materials for Proton Exchange Membrane Fuel Cell Systems**. American Chemical Society, Asilomar Conference Grounds, Pacific Grove, CA. Contact: James E. McGrath at (540) 231-5976, jmcgrath@vt.edu. See: www.chemistry.org/portal/Chemistry

MAR

3-6	**SAE 2003 World Congress**. Cobo Center, Detroit, MI. Contact: (724) 776-4841. See: www.sae.org/congress.
4-6	**14th Annual U.S. Hydrogen Meeting: Energy Security Through Hydrogen**. National Hydrogen Association, Capital Hilton Hotel, Washington, DC. Contact: Laura Neer at (202) 233-5547, (202) 223-5537 (fax), nha@ttcopr.com. See: www.hydrogenconference.org.
4-6	**Electric Power 2003**. Co-located conferences include HRSG Users' Group, PRB Coal Users' Group, ASME FACT Division and Cooling Technology Institute Owner/Operator Council. George R. Brown Convention Center, Houston, TX. Contact: (713) 463-9595. See: www.electricpowerexpo.com.
12-14	**Power Systems Conference 2003: Distributed Generation and Advanced Metering**. Madren Center, Clemson University, Clemson, S.C. Contact: Dr. Adly Girgis at PCS@ces.clemson.edu.
17-18	**Fuel Cell Investment Summit**. The Connecticut Clean Energy Fund, Mohegan Sun Casino, Uncasville, CT. Contact: (860) 563-0015.
18	**2003 International Conference on Innovative Materials-Business & Investment**. Shanghai, China. Contact: Chen Qian at qchen@materials.gov.cn.
18-19	**Fuel Cells for Stationary Applications**. Central London, UK. See: www.marcusevansuk.com.
18-20	**World Workplace 2003**. International Facility Management Association, Yokohama, Japan. Contact: www.worldworkplace.org/japan/index.htm.
23-27	**ACS Symposium - Fuel Clean-Up Considerations for Fuel Cell Applications: Clean Power in 21st Century**. American Chemical Society, Morial Convention Center, New Orleans, LA. Contact: Sai P. Katikaneni at (203) 825-6067, skatikaneni@fce.com. See: http://oasys2.confex.com/acs/225nm/topics.html.

APR

30-1	**18th Annual Platts Global Power Markets Conference**. Fairmont Hotel, New Orleans, LA. Contact: (720) 548-5668, laurel_zimmer@platts.com. See: www.globalpower.platts.com.
6-9	**2003 Code Official Institute and Spring Meeting Education Program**. International Code Council, Sheraton Overland Park Hotel, Overland Park, KS. Contact: (708) 799-7790.
7-12	**Hannover Fair '03, Group Exhibit Hydrogen + Fuel Cells Showcase**. Hanover, Germany. Contact: Arno Evers at +49.8151.998923, +49 8151 998 9243 (fax), arno@fair-pr.com. See: www.live-fair.com/hm03/index.html.
21-23	**1st International Conference on Fuel Cell Science, Engineering and Technology**. American Society of Mechanical Engineers, Rochester Institute of Technology Inn and Conference Center, Rochester, NY. Contact: (212) 591-7789, (212) 591-7059 (fax), fuelcell@asme.org. See: www.asme.org/fuelcell.
28-30	**MAWTEC XI, 11th North American Waste to Energy Conference**. Mariott Waterside, Tampa, FL. Contact: (212) 591-7797.

MAY

18-21	**9th National Clean Cities Conference and Exposition**. Wyndham Palm Springs Resort, Palm Springs, CA. See: www.ccities.doe.gov/conference.shtml.
18-22	**NFPA World Safety Conference & Exposition and 6th World Congress of the World Organization of Building Officials**. Dallas Convention Center, Dallas, TX. Contact: Margie Coloian or Julie Reynolds at (617) 984-7275. See: www.nfpa.org.
19-22	**Hydrogen, Fuel Cells & Infrastructure Technologies Program Review and Peer Evaluation**. Berkeley, CA. See: www.eren.doe.gov/hydrogen.
28-29	**Fuel Cells Summit VII**. University of Maryland Inn & Conference Center, Adelphi, Maryland. Hosted by the U.S. Department of Energy. Contact: Maude Wickline at (703) 617-4254, maude.wickline@pnl.gov. See: www.pnl.gov/fuelcells.

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systems approaching the lower density targets, but development efforts continue to provide a cost-effective reprocessing method. Reversible solid-state hydrogen storage materials can also be thought of as falling into two broad categories: (1) adsorption materials, generally carbon-based, where hydrogen is bonded on the surface and (2) absorption materials, generically called hydrides, where hydrogen resides in the bulk of the material.

Carbon is a plentiful, lightweight, and low-cost material that can be synthesized into many different forms and physical structures. Development efforts are currently focused on single-wall carbon nanotubes (SWNT) as a storage material. This structure will yield the highest adsorbed hydrogen density because the nanotubes are essentially one atomic plane thick; that is, the surface-to-volume ratio is as good as it gets! Several laboratories are active in this field and current results show promising performance in terms of storage densities. Of all the storage options, this option is perhaps in the earliest developmental phases and thus considerable time will be needed to determine commercial viability. Nevertheless, it has great promise as an effective storage material.

Hydrides, particularly intermetallic and high-temperature hydrides, have been studied for many years. Although these materials have high energy densities, typically about 10 MJ per liter, they are heavy and relatively expensive. Intermetallic hydrides all have hydrogen capacities in the range of 1.5 to 2 wt.% H_2, which is far too heavy for vehicular applications. In addition, the high-temperature hydrides require operating temperatures above those available as waste heat on vehicles.

More recently, certain complex hydrides have been found to exhibit reversible behavior after doping with Ti and other elements. Sodium alanate ($NaAlH_4$) in particular has been studied in some detail within the last several years and has been shown to have a reversible hydrogen storage capacity of 4.5 to 5 wt.% H_2. This storage capacity is significantly better than intermetallic hydrides but still short of the energy density needs for vehicles. Current development is aimed at understanding the behavior of these complex hydrides and in finding similar materials with greater capacity.

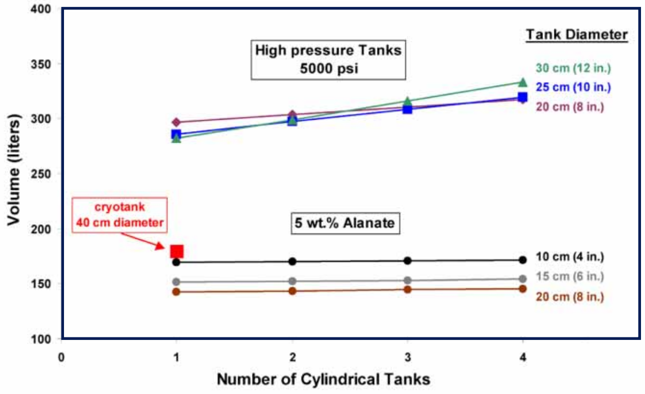
Summary

How do these storage options stack up against one another? The plots are the estimated volumes and weights of storage systems for storing 5 kg of hydrogen using compressed gas, cryogenic storage, and sodium alanate. If the packing densities of SWNTs are about the same as the alanate powder, then the plots would be roughly equivalent for this storage media as well. Note that the overall volume depends on how the system is fabricated in terms of cylinder diameter and number of cylinders.

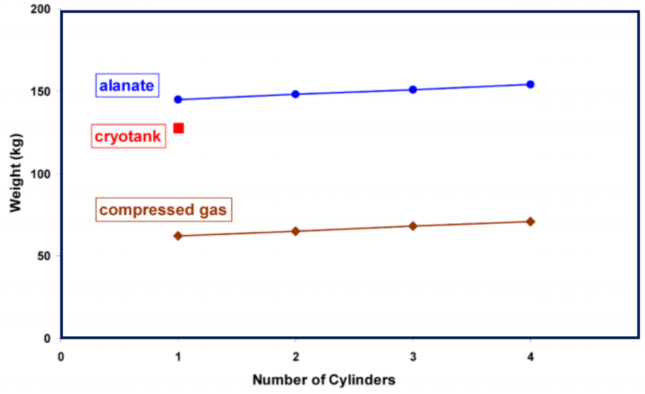
As expected, the highest density approaches result in the smallest volumes. Only a single cylinder was considered for the cryogenic system because the surface-to-volume ratio for heat loss considerations should be minimized. The solid-state and cryogenic systems are close to the lower target value for volumetric density. In terms of weight, however, the compressed gas tanks exceed the lower target value, while the solid-state systems are almost a factor of two too heavy.

In addition to energy densities, numerous other factors–cost, safety, manufacturability, cycling performance, impurity effects–apply to storage systems. Currently none of the systems satisfy all the requirements needed to gain wide acceptance by consumers. Rapid advances have been made in recent years and ongoing development programs hold great promise for improving storage systems for use in future fuel cell applications.

System Volumes for Storing 5kg Hydrogen



System Weights for Storing 5kg Hydrogen



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EERE Releases Strategic Plan for Addressing Nation's Energy Challenge

The Office of Energy Efficiency and Renewable Energy (EERE) has released its Strategic Plan in response to Secretary of Energy Spencer Abraham's challenge to revolutionize how we approach energy efficiency and renewable energy technologies.

The plan describes EERE's nine strategic goals for realizing its vision, its strategies for achieving those goals, and some of the indicators it will use to measure success.

The Strategic Plan also discusses EERE's new streamlined, integrated, and focused management structure designed to meet the *President's Management Agenda* for 2002 calling for management improvements throughout the Federal government. The new structure is built on 11 programs designed to accomplish EERE's goals and a business administration office that supports the programs.

To obtain a copy of the EERE Strategic Plan, visit www.eren.doe.gov/eere/pdfs/fy02_strategic_plan.pdf

National Hydrogen Energy Roadmap Now Available!

The U.S. Department of Energy (DOE) recently published the *National Hydrogen Energy Roadmap* as the second step in its National Hydrogen Vision and Roadmap process. The roadmap outlines key issues and challenges in developing hydrogen energy and suggests paths that government and industry can take to expand the use of hydrogen-based energy.

The roadmap lists several cross-cutting issues that will influence a whole-system approach to designing and implementing a hydrogen-based energy system.

The roadmap also discusses the following segments of a hydrogen energy system, providing a description of the current status, challenges to achieving the vision, and paths forward for each segment:

- Production
- Delivery
- Storage
- Conversion
- Applications
- Education and Outreach
- Codes and Standards

For more information or to download a copy of the vision document or roadmap, visit the DOE Hydrogen Information Network website at www.eren.doe.gov/hydrogen.

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Publications on Efficiently Constructing Hydrogen Fueling Stations Available Soon

The handbook provides detailed, nontechnical descriptions of five representative hydrogen fueling station facilities in the United States:

1. Chicago Transit Authority (CTA) in Chicago, IL
2. California Fuel Cell Partnership (CaFCP) in West Sacramento, CA
3. SunLine Transit Agency in Thousand Palms, CA
4. Ford Motor Company in Dearborn, MI
5. American Honda in Torrance, CA.

The CTA, CaFCP, and Ford hydrogen fueling stations receive and store liquid hydrogen, produced by steam reforming natural gas, from a chemical company via cryogenic liquid tanker trailers, convert the liquid hydrogen to gas and store it at pressures ranging from 3600 to 5000+ psi, and dispense the hydrogen into their fleets of experimental fuel cell-powered vehicles.

The hydrogen fueling stations operated by American Honda and SunLine Transit are unique in that at least some of the hydrogen they dispense is generated onsite by the electrolysis of water using electricity from the grid and/or from an array of photovoltaic solar cells. However, the fuel dispensing system and process for these two projects is similar to those used by CTA, CaFCP, and Ford.

Clearly, codes and standards that address fire prevention and safety-related issues for operators and consumers are crucial to designing, siting, constructing, and operating cost-effective hydrogen fuel stations and NREL envisions expanding the collaboration to include the International Code Council (ICC). The guidebook will reference existing codes and standards related to hydrogen fuel stations, and will point out requirements for which appropriate codes and standards do not exist but are needed.

Currently, the handbook is in the DOE/NFPA/NREL internal review process. When completed, representative building code and fire safety officials will critically review the handbook. The handbook is expected to be publicly available by June 2003. Plans call for completing the guidebook by July 2003.

For additional information, contact Russell Hewett at the National Renewable Energy Laboratory (NREL) at (303) 384-7463, (303) 384-7495 (fax), or email at russell_hewett@nrel.gov.

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