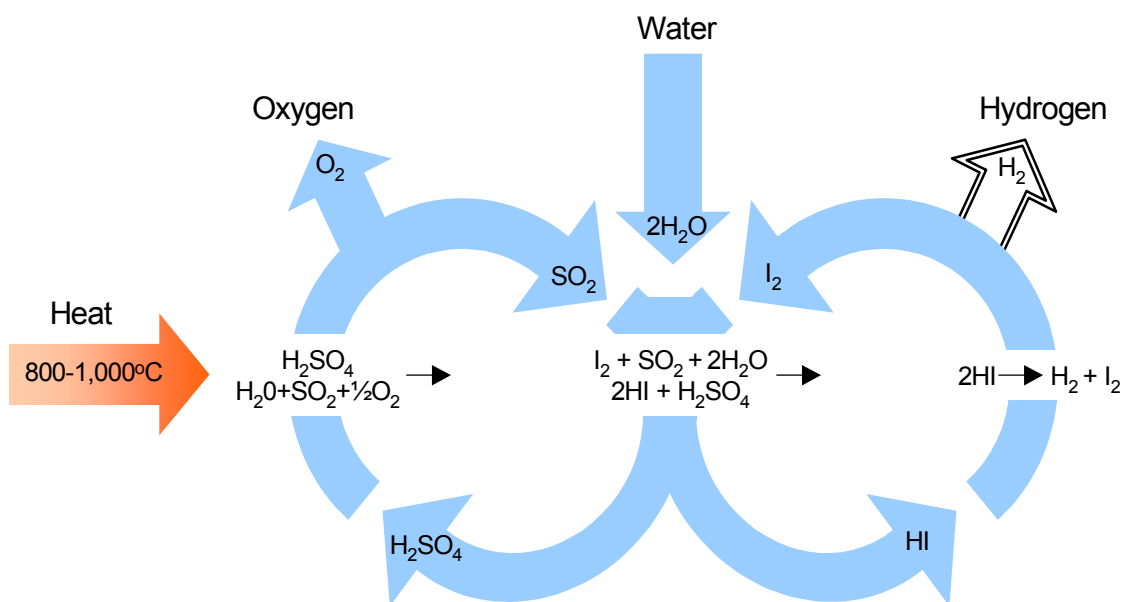


## 2.2 HYDROGEN

### 2.2.1 HYDROGEN PRODUCTION FROM NUCLEAR FISSION AND FUSION

#### Technology Description



Hydrogen is a carbon-free fuel that can be produced from hydrogen-containing compounds, such as fossil fuels or water, and used in vehicles, homes, businesses, and power plants, or as a chemical feedstock. When hydrogen is produced from fossil fuels, CO<sub>2</sub> appears as a concentrated byproduct. However, advanced nuclear fission and fusion systems can be used to produce hydrogen without generating CO<sub>2</sub>. Very high-temperature, high-efficiency nuclear power plants can either produce electricity to electrolyze water vapor or supply high-temperature process heat to drive chemical cycles for hydrogen production. Implementing these hydrogen-production technologies will reduce carbon emissions significantly below what is possible with nuclear-generated electricity alone.

#### System Concepts

- Very high-temperature, high-efficiency nuclear systems can be used to produce hydrogen either by electrolysis of water vapor or chemical cycles for water decomposition.

#### Representative Technologies

- Advanced, high-temperature fission reactors such as those being developed by the Generation IV Nuclear Energy Systems Initiative (including high-temperature gas-cooled reactors)
- Fusion reactor using gas, liquid-metal, or molten-salt cooling.

#### Technology Status/Applications

- Very high-temperature reactors cooled by gas or molten salts are being developed.
- Fusion technology is in development and making steady progress.
- Gas-cooled reactors operate in Japan at the temperatures of interest.
- Chemical cycles for the decomposition of water to yield hydrogen are being developed.
- Electrolysis of water vapor rather than liquid water is being developed.
- Fuel-cell-powered vehicles using hydrogen are being developed and demonstrated by industry in partnership with the Department of Energy.

#### Current Research, Development, and Demonstration

#### RD&D Goals

- By 2030, reduce thermochemical facility costs by two-thirds by 2030 and high-temperature electrolysis facility costs by 85% in the same time frame.

- By 2030, decrease operating costs by three-fourths for both technologies, while thermal efficiency would increase from levels as low as 30% to 40% to more than 50%.

**RD&D Challenges**

- Develop reactor designs and materials that operate at temperatures high enough to achieve needed efficiencies.
- Overcome barriers to economic hydrogen generation by electrolysis.
- Develop chemical processes for water decomposition that operate efficiently and reliably.
- Demonstrate production and large-scale storage of hydrogen using a nuclear power plant.

**RD&D Activities**

- Development of high-temperature materials, separation membranes, advanced heat exchangers, and supporting systems relating to hydrogen production using the sulfur-iodine (S-I) thermochemical cycle and high-temperature electrolysis.
- Design and development of gas-cooled and lead-bismuth-cooled reactors and hydrogen-production systems are underway, through the Generation IV Nuclear Energy Systems Initiative and the Nuclear Hydrogen Initiative.
- Concept development for high-temperature blanket/cooling systems is underway as part of the fusion program.

**Recent Progress**

- Chemical cycles for hydrogen production are being developed, and the conceptual design is being prepared for a gas-cooled reactor to couple to the most promising cycles.
- Japan’s gas-cooled, high-temperature test reactor operates at 850°C with periodic testing up to 950°C.
- Recent analyses indicate that, because of low fuel costs, fission systems could provide cost-effective off-peak electricity for electrolysis at either onsite or offsite filling stations.

**Commercialization and Deployment Activities**

- High-temperature, high-efficiency test reactors are being operated in China and Japan.
- Fuel cell-powered vehicles will create demand for hydrogen in addition to existing demand of the process chemical and petrochemical industries.
- High-temperature reactor designs are being developed through the Generation IV Nuclear Energy Systems Initiative. High-temperature operation will make reactors competitive with other methods of electrical power generation.
- Partnering with industry to demonstrate hydrogen production using electricity during off-peak demand periods has been proposed.
- Fusion plants could be commercialized late in the second quarter of this century.

**Market Context**

- The potential for carbon emissions reductions using these technologies is enormous, including consideration of the GHG reduction from the significant improvements in the efficiency of electrical power generation.
- Hydrogen fuel cell vehicles will create a demand for hydrogen as a transportation fuel in addition to the demand by the process chemical industry. Petrochemical industry demand for hydrogen will grow as the use of lower-quality crude oils becomes more common in refining.
- Extends the applicability of large fission energy resources and essentially unlimited fusion energy resources to the transportation sector.

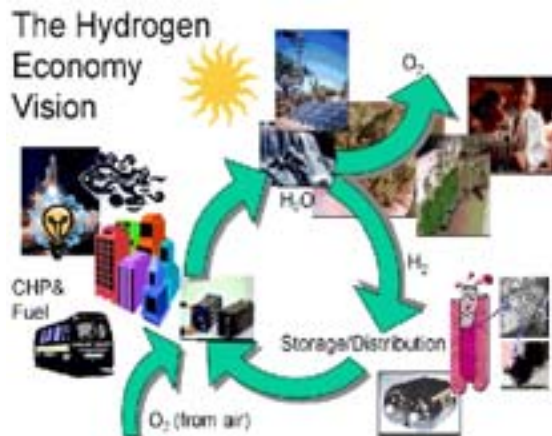
## 2.2.2 HYDROGEN SYSTEMS TECHNOLOGY VALIDATION

### Technology Description

Similar to electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Hydrogen and electricity can be converted from one to the other using electrolyzers (electricity to hydrogen) and fuel cells (hydrogen to electricity). Hydrogen is an effective energy-storage medium, particularly for distributed generation.

Implementation of hydrogen energy systems could play a major role in addressing climate challenges and national security issues through 2030 and beyond. Today, hydrogen is produced primarily from natural gas using widely known commercial thermal processes. In the future, we can adapt current technologies to produce hydrogen with significantly reduced CO<sub>2</sub> emissions, through carbon capture and sequestration processes, and by using renewable and nuclear electricity to produce hydrogen with no production-side CO<sub>2</sub> emissions. Using hydrogen in combustion devices or fuel cells results in few, if any, harmful emissions.

In the next 20-30 years, hydrogen systems used for stationary and vehicular applications could solve many of our energy and environmental security concerns. Hydrogen could be affordable, safe, domestically produced, and used in all sectors of the economy and in all regions of the country.



#### System Concepts and Representative Technologies

- A hydrogen system is comprised of production, storage and distribution, and use. A systems approach is needed to demonstrate integrated hydrogen production, delivery, and storage, as well as refueling of hydrogen vehicles and use in stationary fuel cells. This could involve providing hydrogen in gaseous and liquid form. Technologies are in various stages of development across the system. Hydrogen made via electrolysis from excess nuclear or renewable energy can be used as a sustainable transportation fuel or stored to meet peak-power demand. It also can be used as a feedstock in chemical processes.
- Hydrogen produced by decarbonization of fossil fuels followed by sequestration of the carbon can enable the continued use of fossil fuels in a clean manner during the transition to the ultimate carbon-free hydrogen energy system.
- For hydrogen to become an important energy carrier – as electricity is now – an infrastructure must be developed. Although the ultimate transition to a hydrogen economy requires significant infrastructure investments, it is possible to develop the components of a hydrogen energy system in parallel with infrastructure. As hydrogen applications become more cost effective and ubiquitous, the infrastructure will also evolve. Beginning with fleets of buses and delivery vans, the transportation infrastructure will evolve to include sufficient refueling islands to enable consumers to consider hydrogen vehicles as attractive and convenient. The development of distributed power systems will begin with natural gas-reformer systems and evolve to provide hydrogen from a variety of resources (for all services), including hydrogen-to-fuel vehicles, reliable/affordable power, lighting, heating, cooling, and other services for buildings and homes.
- The technology-validation effort also provides information in support of technical codes and standards development of infrastructure safety procedures.

#### Technology Status/Applications

- Today, hydrogen is primarily used as a chemical feedstock in the petrochemical, fertilizer, electronics, and metallurgical processing industries. Hydrogen is receiving new capital investments for transportation and power-generation applications.
- Nearly half of the worldwide production of hydrogen is via large-scale steam reforming of natural gas, a relatively low-carbon fuel/feedstock. In the United States, almost all of the hydrogen used as a chemical (i.e., for petroleum refining and upgrading, and ammonia production) is produced from natural gas. Today,

we safely produce about 9 million metric tons of hydrogen annually. Although comparatively little hydrogen is currently used as fuel or as an energy carrier, there are emerging trends that will drive the future consumption of hydrogen.

- The long-term goal of the DOE Hydrogen, Fuel Cell & Infrastructure Technologies (HFCIT) Program is to make a transition to a hydrogen-based energy system in which hydrogen will join electricity as a major energy carrier. Furthermore, the hydrogen will be derived from domestically plentiful resources, making the hydrogen economy an important foundation for sustainable development and energy security.
- Requirements in California – especially the Los Angeles basin – are propelling the development of zero-emission vehicles, which in turn, provide incentives for the growth of fuel cell cars, trucks, and buses. Several bus fleets are currently incorporating hydrogen and fuel cell technologies into their fleets. Major car manufacturers are developing fuel cell vehicles in response to concerns about greenhouse gas and other emissions, and in response to policy drivers, especially for higher efficiencies and reduced oil consumption.
- Integrating the components of a hydrogen system in a variety of applications enables the continued development of infrastructure that is needed as we move from concept to reality. The development of the components of an integrated hydrogen system has begun:
- *Production:* Hydrogen production from conventional fossil-fuel feedstocks is commercial, and results in significant CO<sub>2</sub> emissions. Large-scale CO<sub>2</sub> sequestration options have not been proven and require R&D. Current commercial electrolyzers are 60%-70% efficient, but the cost of hydrogen is strongly dependent on the cost of the electricity used to split water into hydrogen and oxygen. Production processes using wastes and biomass are under development, with a number of engineering scale-up projects underway. Longer-term, direct hydrogen production processes (photoconversion) are largely in the research stage, with significant progress being made toward development of cost-effective, efficient, clean systems.
- *Storage and Distribution:* Liquid and compressed gas tanks are available and have been demonstrated in a small number of bus and automobile demonstration projects. Lightweight, fiber-wrapped tanks have been developed and tested for higher-pressure hydrogen storage. Experimental metal hydride tanks have been used in automobile demonstrations. Alternative solid-state storage systems using alanates and carbon nanotubes are under development. Current commercial practices for the distribution and delivery of hydrogen include cryogenic liquid and high-pressure trucks, and limited pipeline transmission. Longer-term, lower-cost delivery infrastructure and technologies will be needed.
- *Use:* Significant demonstrations by domestic and foreign auto and bus companies have been undertaken in Japan, Europe, and the United States. Small-scale power systems using fuel cells are being beta-tested. Small fuel cells for battery replacement applications have been developed.

### **Current Research, Development, and Demonstration**

#### **RD&D Goals**

- The overall goal in this area is to validate, by 2015, integrated hydrogen and fuel cell technologies for transportation, infrastructure, and electric generation in a systems context under real-world operating conditions.
- By 2005, demonstrate that an energy station (coproduction of hydrogen as fuel for a stationary fuel cell and for a fuel-cell vehicle) can produce electricity for 8 cents/kWh and \$3.60/gallon gasoline equivalent.
- By 2008, demonstrate stationary fuel cells with a durability of 20,000 hours and 32% efficiency.
- By 2009, demonstrate vehicles with greater than 250-mile range and 2,000-hour fuel cell durability.
- By 2009, establish hydrogen production at \$3/gallon gasoline equivalent.
- By 2015, provide critical statistical data that demonstrate that fuel cell vehicles can meet targets of 5,000-hour fuel cell durability, storage systems can efficiently meet 300+ mile range requirements, and H<sub>2</sub> fuel can cost less than \$2.50/gallon gasoline equivalent.
- The technology validation effort also will provide sufficient information in support of technical codes and standards development of infrastructure safety procedures.

#### **RD&D Challenges**

- Low-cost and durable fuel cells need to be developed and demonstrated that can make significant market penetrations in the transportation and electric-generation sectors.

- Low-cost, low-weight, and high energy-density storage systems need to be developed so that there is no compromise to vehicle costs and existing vehicle passenger or trunk compartments.
- Hydrogen can be produced and delivered at a cost that is competitive on a cents/mile basis with current vehicles.
- Codes and standards must be developed and implemented.

#### **RD&D Activities**

- The overall strategy of the HFCIT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation using close collaboration with industry that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps determine the performance and cost targets that technologies must meet to achieve goals of the HFCIT Program, as well as specific project objectives determined by peer review.
- DOE's HFCIT Program is carried out by national laboratories, universities, and the private sector, including cost-shared industry-led efforts, and CRADA collaborations between industry and the labs.

#### **Recent Progress**

- Hydrogen refueling equipment (liquid delivered to the facility) – to provide hydrogen to the small fleet of hydrogen fuel cell vehicles that are currently being tested in California – has been installed by the California Fuel Cell Partnership (Sacramento, California).
- Three Power Park facilities that generate power from fuel cells and engines and hydrogen fuel for vehicles have been built and are being tested. Natural gas, biomass, wind, and solar energy are being used to generate the hydrogen fuel for both stationary power and for vehicles.
- An Energy Station that coproduces hydrogen fuel from natural gas for both stationary and vehicles applications has been demonstrated.
- Four awards have been made to major automobile and energy company teams to demonstrate up to 120 vehicles and 28 stations that will validate program targets under real-world operating conditions.

#### **Commercialization and Deployment Activities**

- Major industrial companies are pursuing R&D in fuel cells and hydrogen reformation technologies with a mid-term (5-10 years) time frame to deploy these technologies for both stationary and vehicular applications. These companies include ExxonMobil, Shell, Chevron Corporation, BP, General Motors, Ford, Daimler-Chrysler, Hyundai, Toyota, Honda, Nissan, BMW, United Technology Corporation Fuel Cells, Ballard, Air Products, and Praxair.
- The National Vision of America's Transition to a Hydrogen Economy, completed in November 2002, outlines a vision for America's energy future – a more secure nation powered by clean, abundant hydrogen. This document was used as the foundation for formulating the elements of the National Hydrogen Energy Roadmap.
- The Fuel Cell Report to Congress, completed in February 2003, was a request from Congress that DOE report (within 12 months) to the House and Senate Committees on Appropriations, on the technical and economic barriers to the use of fuel cells in transportation, portable power, stationary, and distributed power generation applications.
- In November 2002, the U.S. Department of Energy issued its National Hydrogen Energy Roadmap. The purpose of the roadmap was to identify the activities required to realize hydrogen's potential to address U.S. energy security, diversity, and environmental needs.
- The DOE Office of Energy Efficiency and Renewable Energy (EERE) – with support from the DOE Offices of Fossil Energy; Science; and Nuclear Energy, Science, and Technology – completed a Hydrogen Posture Plan in response to the President's Hydrogen Fuel Initiative. This document outlines the activities, milestones, and deliverables that the Department plans to pursue to support America's shift to a hydrogen-based energy system.
- The DOE Hydrogen, Fuel Cells, and Infrastructure Technologies Program completed a Multiyear Research, Development, and Demonstration (RD&D) Plan in February 2005, detailing the goals, objectives, technical

targets, tasks, and schedule for EERE's contribution to the DOE Hydrogen Program.

- The DOE Office of Fossil Energy (in June 2003) completed the FE Hydrogen Program Plan, focusing on the research, development, and demonstration activities that are required to develop advanced hydrogen production, storage, and delivery technologies from fossil fuels.
- The Basic Research Needs for the Hydrogen Economy, completed by the DOE Office of Basic Energy Sciences in 2003, outlines the findings from the Basic Energy Sciences Workshop on Hydrogen Production, Storage, and Use.
- The DOE Nuclear Energy, Science, and Technology Program completed the Nuclear Hydrogen R&D Plan in March 2004 to identify the candidate advanced hydrogen production technologies most suitable for nuclear energy, assess their viability, and prioritize the needed R&D to enable the demonstration of nuclear hydrogen production. The DOE Nuclear Energy, Science, and Technology Program also completed the Nuclear Hydrogen Initiative Ten-Year Program Plan in March 2005, identifying objectives and priorities to provide programmatic direction within the U.S. Department of Energy (DOE) and among the program participants or collaborators, including national laboratories, industry, universities, and international participants.

## 2.2.3 HYDROGEN PRODUCTION AND DISTRIBUTION USING ELECTRICITY AND FOSSIL/ALTERNATIVE ENERGY

### Technology Description

Similar to electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Today, industrial hydrogen is produced primarily from natural gas using widely known commercial thermal processes. In the future, we can adapt current technologies through advanced development to produce hydrogen with significantly reduced overall CO<sub>2</sub> emissions, through carbon capture and sequestration – and by using renewable and nuclear electricity to produce hydrogen with no production-side CO<sub>2</sub> emissions.

### System Concepts and Representative Technologies

- Natural gas can be delivered to refueling stations using existing pipelines and re-formed into hydrogen on-site. The infrastructure costs for small-scale, distributed production would be much lower than that required to pipe or truck mass-produced hydrogen from long distances. By making hydrogen from natural gas, we can also take advantage of existing natural gas infrastructure such as storage cylinders, pipelines, and compressors.
- Hydrogen made via electrolysis from nuclear or renewable power can be used as a sustainable transportation fuel or stored to meet peak-power demand. Hydrogen as a storage medium enables intermittent renewable power systems to provide reliable power, even when the wind is not blowing or the sun is not shining.
- Hydrogen produced from fossil fuels (followed by sequestration of the carbon) can enable the continued use of fossil fuels in a clean manner during the transition to the ultimate carbon-free hydrogen energy system.
- Biomass can be used to produce hydrogen, electricity, and other value-added coproducts such as activated carbon, fuel additives, and adhesives, when it is thermally treated under relatively mild conditions. This is part of the biorefinery concept, wherein fuels, power, and products are produced from biomass resources in an integrated process.
- Hydrogen separation- and purification-process improvements offer cost-reduction and efficiency improvement opportunities for current fossil-based systems.
- An ultimate hydrogen economy vision includes hydrogen production from several processes, including high-temperature thermochemical water splitting cycles, direct photoelectrochemical semiconductor-based systems, and biological systems.
- Transport and distribution concepts and technologies include evaluation of existing natural gas pipelines for use to transport hydrogen and natural gas mixtures or pure hydrogen, development of new pipeline materials to reduce costs and resolve hydrogen embrittlement issues, development of more reliable and lower-cost hydrogen-compression technologies, development of more energy-efficient and lower-cost hydrogen liquefaction technology, and the evaluation of novel solid or liquid carriers for hydrogen delivery.

### Technology Status/Applications

- Nearly half of the worldwide production of hydrogen is via large-scale steam reforming of natural gas (a relatively low-carbon fuel/feedstock). In the United States, almost all of the hydrogen used as a chemical (i.e., for petroleum refining and upgrading, ammonia production) is produced from natural gas. Today, we produce and utilize 9 million metric tons of hydrogen annually in the United States. Although comparatively little hydrogen is currently used as fuel or as an energy carrier, there are emerging technologies such as fuel cells that will drive the future consumption of hydrogen into the transportation and electric-generation sectors.
- Hydrogen production from conventional fossil-fuel feedstocks is commercial (on a large scale), but results in significant CO<sub>2</sub> emissions.
- Current commercial electrolyzers are 60%-70% efficient, but the cost of hydrogen is strongly dependent on the cost of electricity.
- Biomass feedstocks (such as agricultural and forest residues, switchgrass and willow trees, and municipal waste) are being evaluated and tested for dedicated hydrogen production and multiproduct biorefineries.

### Current Research, Development, and Demonstration

- Today, hydrogen is transported by cryogenic liquid truck and high-pressure tube trailers at a very high cost. Some is transported through a very limited hydrogen pipeline infrastructure. Research on lower-cost hydrogen distribution technologies is just now being initiated.



Hydrogen production by photovoltaic hydrolysis.

#### RD&D Goals

- By 2006: (1) completion of research of small-scale steam methane reformers with a projected cost of \$3.00/kg hydrogen at the pump; (2) development of alternative reactors, including auto-thermal reactors; and (3) evaluation of whether renewable energy integrated hydrogen production by water electrolysis can achieve 64% net energy efficiency at a projected cost of \$5.50/kg, delivered at 5,000 psi.
- By 2010: At the pilot-plant scale, demonstrate (1) membrane separation and reactive membrane separation technology for hydrogen production from coal, and (2) distributed hydrogen production from natural gas with a projected cost of \$2.50/kg hydrogen at the pump.
- By 2015: At the laboratory-bench scale, demonstrate (1) a photo-electrochemical water-splitting system and (2) a biological system for water-splitting (or other substrates) that both show potential to achieve long-term costs that are competitive with conventional fuels and reduce the cost of hydrogen distribution to \$1/kg.

#### RD&D Challenges

- Key challenges to commercializing small-scale distributed production technology are: (1) reducing the capital equipment costs; (2) reducing the cost of operating and maintaining these systems; and (3) using components that can withstand wide temperature ranges under which these systems operate.
- Electrolyzers operating at higher temperatures could provide more cost-effective hydrogen (higher efficiency/reduced electricity demand). Integration with intermittent renewable resources requires development of control strategies and/or design modifications.
- Improved heat and process integration as well as improved catalyst and membrane technology is needed to reduce the cost and improve the energy efficiency for the production of hydrogen from biomass.
- Hydrogen production via chemical cycles using high-temperature heat from nuclear power plants or solar collection facilities will need to be developed and then demonstrated.
- Photoconversion R&D efforts – including photoelectrochemical and photobiological processes – are presently in the exploratory research stage. Biological production of hydrogen from other substrates is also in the exploratory research stage. To continue advancing these technologies, research must be supported.
- Pipeline development to reduce pipeline capital and installation costs while resolving hydrogen embrittlement issues.

#### RD&D Activities

- The overall strategy of the HFCIT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation using close collaboration with industry that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps determine the performance and cost targets that technologies must meet to achieve goals of the HFCIT Program – as well as specific project objectives determined by peer review.
- DOE's HFCIT Program is carried out by national laboratories, universities, and the private sector, including cost-shared industry-led efforts, and CRADA collaborations between industry and the labs.

### Recent Progress

- Air Products and Chemicals Inc. achieved a three times reduction in hydrogen purification cost compared with commercially available units



- GE Global Research completed R&D for a highly efficient autothermal cyclic reformer for integration into the hydrogen generation system.
- Gas Technology Institute (GTI) developed a second-generation fuel processor and a hydrogen filling station with a fast-fill dispensing system.
- These three efforts indicate that the technology is approaching \$3/gge for dispensed hydrogen from natural gas (690 kg/day, >100 units annually, \$4/MMBTU NG, 90% utilization).
- An autothermal reformer was installed and operated at a transit agency in California to generate hydrogen for buses and other vehicles. Also at this facility, a PV-electrolysis system is operated to provide renewable hydrogen to the same vehicles.
- Increased photobiological efficiency of absorbed sunlight energy to ~15% (5% in 2003), found the first designer proton-channel gene, and designed the DNA sequence for the necessary proton channel to increase system efficiency
- Achieved 1,000 hours durability (100 hour in 2003) with new gallium nitride material for photoelectrochemical hydrogen production
- Oak Ridge National Laboratory (ORNL) developed a new proton transport membrane that – when used in a less capital intensive, single-step reactor – could cost about a quarter less than conventional hydrogen-purification technologies.
- Air Products and Chemicals Inc. fabricated a commercial-size ceramic membrane and operated a pilot scale prototype at 24 MSCFD of hydrogen.
- The National Renewable Energy Laboratory (NREL) developed a new catalyst for biomass gasification with reduced coking and improved attrition characteristics.
- More than 150 potential thermochemical cycles have been identified and have been screened for energy efficiency and practicality for use with solar concentrators to produce hydrogen from water and sunlight. Four families of cycles have been selected and are being researched.

#### **Commercialization and Deployment Activities**

- In an industry-university-national lab partnership, agricultural residues are being used to produce hydrogen and valuable coproducts. Peanut shells represent both a waste-disposal issue and a valuable resource. Pyrolysis of the densified shells results in a valuable vapor stream that can be used to produce chemicals and hydrogen, and in a solid stream that is used to make activated carbon. This concept is currently being tested in a pilot plant, in preparation for operation at an industrial site in Georgia.
- An industry-led project is installing a small-scale steam methane reformer to provide hydrogen for vehicles in the Las Vegas, Nevada, area.

## 2.2.4 HYDROGEN STORAGE

### Technology Description

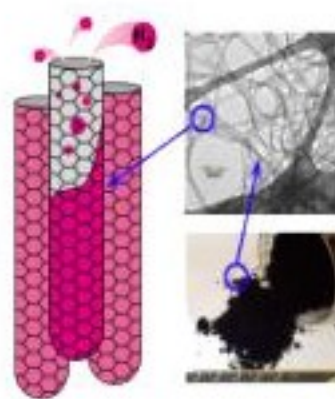
Unlike electricity, hydrogen can be stored for long periods of time without significant losses. Today, hydrogen is stored as a cryogenic liquid or compressed gas, and transported by cryogenic liquid or high-pressure trucks; and, to a limited extent, by gaseous pipelines. In the future, it could be stored and possibly transported in chemical and metal hydrides, carbon nanostructured materials, and high surface area adsorbents. In such forms, hydrogen would be more amenable to safe and efficient distribution and storage. In the meantime, current technologies can be adapted to store and distribute hydrogen to the emerging transportation and stationary markets for hydrogen.

#### System Concepts and Representative Technologies

- There are four broad hydrogen storage approaches currently under development: (1) composite pressure vessels, which will contain the hydrogen as a compressed gas or cryogenic vapor; (2) physical absorption on high-surface-area lightweight carbon structures; (3) reversible metal hydrides; and (4) chemical hydrides. Improving hydrogen compression and/or liquefaction equipment – as well as evaluating the compatibility of the existing natural gas pipeline infrastructure for hydrogen distribution – are also planned.
- Materials-based approaches such as solid-state materials or liquids may offer increased safety for onboard vehicular storage of hydrogen, because tank punctures or ruptures would not result in large energy releases. These approaches also require less volume than pressurized or liquid systems. Stationary applications would also benefit from the successful development of such systems.

#### Technology Status/Applications

- Most prototype vehicles store hydrogen in composite tanks at high pressures (5,000 or 10,000 psi), while some store liquid hydrogen at 20 K. There are limited demonstrations of vehicles with metal hydrides and chemical hydrides, such as sodium borohydride. Metal hydrides are used in limited stationary applications where weight is not a critical factor, and where waste heat is available at the appropriate temperature for hydrogen release.
- Current R&D efforts are focused on improving performance (i.e., weight, volume, charging/discharging rates, cycle life, safety, etc.) and lowering cost.
- Particularly notable are recent advances in storage energy densities, primarily focused on mobile applications. The composite tank development is a prime example of a successful technology partnership among the national labs, DOE, and industry.
- Industrial investment in chemical hydride development has recently been initiated



Carbon nanotube structure and micrographs.



High-pressure, all-composite gaseous hydrogen storage cylinders encourage commercialization of hydrogen gas-powered vehicles.

- Continued improvements are still required to meet perceived customer demands in vehicular applications, in particular with respect to convenience, safety, and cost.

**Current Research, Development, and Demonstration**

**RD&D Goals**

- By 2010, develop and verify hydrogen storage systems with 6 weight-percent, 1,500 watt-hrs/liter energy density, and at a cost of \$4/kWh of stored energy.
- By 2015, develop and verify hydrogen storage systems with 9 weight-percent, 2,700 watt-hrs/liter energy density, and a cost of \$2/kWh of stored energy – and develop the associated technology.

**RD&D Challenges**

- Onboard hydrogen storage for transportation applications requires increased storage density, so that the volume and weight of storage systems can be reduced while providing range equal to that of a conventionally fueled vehicle, without compromising vehicle weight and performance. Technologies that meet performance (capacity, cycle life, charging/discharging kinetics, efficiency, etc.), safety and cost are required.
- Fundamental understanding of chemical and metal hydrides and carbon nanostructured materials as hydrogen storage media is needed to enable the efficient and timely development of storage systems that are inherently safe and more efficient and convenient than current systems.
- Research and development of advanced materials-based hydrogen storage systems – including chemical hydrides, metal hydrides, such as amides and complex metal hydrides, and carbon materials – needs to be broadened, with deployment of the resultant systems in prototype vehicles and/or at user sites.
- Thermal management, particularly for metal hydride systems, is critical to meet required refueling times. Efficiency and energy requirements to release hydrogen from storage systems must also be addressed.
- Production processes for materials-based technologies need to be developed and scaled-up with industry.
- Off-board regeneration efficiency for chemical hydrogen storage needs to be improved and life-cycle energy and environmental impact needs to be assessed.
- For the interim approach of physical storage, low-cost tanks that meet safety and performance requirements for high-pressure or cryocompressed storage – as well as improved hydrogen compressors – are needed.
- Improved liquefaction equipment that uses less energy to liquefy hydrogen compared to conventional processes (where 30%-35% of the energy contained in the hydrogen is required) could provide additional storage options for stationary applications and more energy-efficient and lower-cost transport of hydrogen by cryogenic liquid trucks.
- New hydrogen compression technology to improve reliability and reduce cost.

**RD&D Activities**

- The overall strategy of DOE’s Hydrogen Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation with close industry collaboration that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps determine the performance and cost targets that technologies must meet to achieve the overall goals of the Hydrogen Program, as well as the specific project objectives determined by peer review.
- RD&D for DOE’s Hydrogen Program is carried out by national laboratories, universities, and the private sector, including CRADA collaborations between industry and labs, and cost-shared industry-led efforts.

**Recent Progress**

- “Centers of Excellence” were established in FY 2005 with multiple Federal laboratory, industry, and university partners, focusing collaborative research in the three key areas of metal hydrides, chemical hydrogen storage, and carbon-based materials.
- High-pressure, composite storage tanks have been developed through the combined efforts of industry, national labs, and universities. Building on DOE-funded industry research, these tanks have been tested and certified, and are now being used in prototype hydrogen vehicles.

- A prototype complex metal hydride system for 1 kg of hydrogen was developed using sodium alanate ( $\text{NaAlH}_4$ ) and provides a basis to investigate critical issues such as performance and thermal management. Sodium borohydride ( $\text{NaBH}_4$ ) was demonstrated in a prototype vehicle, and efforts are underway to investigate regeneration efficiency of the spent fuel.
- A novel thermal hydrogen compressor is being developed in an industry-led project. This compressor operates in conjunction with advanced hydrogen production technologies and improves the efficiency and economics of the compression and hydrogen utilization process. The thermal compressor is an absorption-based system that uses the properties of reversible metal hydride alloys to silently and cleanly compress hydrogen; hydrogen is absorbed into an alloy bed at ambient temperature; and, subsequently, is released at elevated pressure when the bed is heated with hot water. Compression energy can be supplied by waste heat or solar hot water.

**Commercialization and Deployment Activities**

- High-pressure tanks (up to 10,000 psi) have been demonstrated in prototype vehicles, and more than 1,500 have been built and tested.
- Through a national laboratory and industry effort, a prototype cryocompressed tank was constructed and is being tested onboard a pickup.
- An industry-led project is developing metal-hydride storage containers for use on scooters, wheelchairs, and other personal mobility products.

## 2.2.5 HYDROGEN USE

### Technology Description

Almost all of the hydrogen produced in the United States each year (about 9 million tons) is currently used as an industrial feedstock, primarily in the fertilizer and petroleum-refining industries. During the next 20-30 years, solutions for energy security and environmental concerns may be based on development of domestic hydrogen-based energy systems for vehicle and electric power applications. Hydrogen's use as an energy carrier is gaining worldwide interest with development of efficient, clean fuel cell systems that could potentially replace the internal combustion engine in vehicles and provide power in stationary and portable power applications. If pure hydrogen is used as a fuel, fuel cells emit only heat and water as byproducts.

Hydrogen can also be used as a cleaner-burning fuel in internal combustion engines (after slight modifications) and in gas turbines or turbine/fuel cell hybrid systems to provide electric power.

A fuel cell is a device that uses hydrogen (or a hydrogen-rich fuel) and oxygen to create an electric current via an electrochemical reaction. This process is inherently much more efficient than combustion processes, which lose a significant amount of the embodied energy in the fuel to heat. A single fuel cell consists of an electrolyte and two catalyst-coated electrodes (a porous anode and cathode) and produces enough electricity for only the smallest applications. To provide the power needed for larger applications – such as powering a vehicle – individual fuel cells are combined in series into a fuel cell stack. A typical fuel cell stack may consist of hundreds of fuel cells. The fuel cell stack is the “heart” of the energy system, which also includes compressor systems, current converters, thermal and water management systems, some stationary applications, and fuel-processor systems.

There are several types of fuel cells currently under development, classified primarily by the kind of electrolyte they employ. Each has its own advantages, limitations, and potential applications. This technology brief will focus on the fuel cells most suitable for transportation and distributed power generation applications – the polymer electrolyte membrane (PEM) fuel cell system. The PEM fuel cell is a low-temperature fuel cell that offers high-power density, low weight and volume, and rapid-start capabilities. It requires a noble-metal catalyst (e.g., platinum) and operates on pure hydrogen. Other types of fuel cells, which are generally more suitable for larger power facilities (e.g., molten carbonate and solid oxide) are covered elsewhere in this report (see sections 2.1.1 and 2.1.3). Hydrogen's use in gas turbines and internal combustion engines is also covered separately in this report (see sections 2.1.2 and 1.1.1).

#### System Concepts and Representative Technologies

- Due to their fast start-up time, low sensitivity to orientation, and favorable power-to-weight ratio, polymer electrolyte membrane (PEM) fuel cells are the current focus for use in light-duty vehicles. Their ability to cycle on and off, provide higher durability due to low-temperature operations, and offer a relatively small footprint also makes them suitable for distributed power applications.
- PEM fuel cell vehicles with electric power trains operating on pure hydrogen supplied to onboard storage systems. These hydrogen vehicles are fueled at distributed refueling stations.
- PEM fuel cell systems for distributed stationary power applications, including backup power units, grid management, power for remote locations, stand-alone power plants for cities or towns, distributed power generation for buildings and industrial facilities, and combined heat and power generation.
- For fuel cells and fuel cell stacks: membrane electrode assemblies and high-temperature membranes, non- or low-platinum catalysts, and bipolar plates.



- Compressor/expander technologies to enable pressurized operation of fuel cells
- Thermal- and water-management technologies to recover and utilize waste heat and water
- Physical and chemical sensors to detect hydrogen leaks and monitor hydrogen purity
- Fuel-flexible fuel processors for stationary applications.

#### **Technology Status/Applications**

- Industrial participation in PEM system development is expanding, with all major automobile manufacturers and several fuel cell-specific companies investing in development and demonstration activities for both vehicles and power generation.
- Current PEM fuel cell systems do not offer the cost or performance required by end users. Researchers and technology developers are working to overcome a variety of technical barriers to make these systems commercially viable.
- Residential PEM fuel cell units, typically 5-7kW in size, are being developed and demonstrated by several companies. PEM fuel cell-powered buses, taxis, and passenger vehicles are also being demonstrated in limited numbers around the world. For the most part, these demonstration units are essentially custom-built by the manufacturers. Facilities to manufacture these systems in large quantities are still in development.

### **Current Research, Development, and Demonstration**

#### **RD&D Goals**

- By 2010, develop a 60% peak-efficient, durable, PEM fuel cell power system for transportation at a cost of \$45/kW, and a distributed generation (50-250 kW) PEM fuel cell system operating on natural gas or propane that achieves 40% electrical efficiency and 40,000 hours durability at \$400-750/kW.
- By 2015, reduce the cost of PEM fuel cell power systems to \$30/kW for transportation systems.

#### **RD&D Challenges**

Cost and durability are the major barriers to fuel cell commercialization. For transportation applications, which have the most stringent cost and durability requirements, fuel cell costs need to be decreased by a factor of 5, and durability needs to be increased by a factor of 3 to be competitive with current vehicle technologies. R&D challenges include:

- Durable electrodes with low precious-metal content
- High-volume fabrication processes for membrane electrode assemblies and bipolar plates
- Improved air electrode performance to raise cell voltage, increase fuel cell stack efficiency, and reduce number of cells per stack
- Membranes that operate at higher temperatures (e.g., 120°C for transportation and 150°C for distributed power) and low humidity to facilitate heat rejection and increase carbon monoxide tolerance of the anode
- Compact, lightweight, efficient balance-of-plant components, such as air compressors, humidifiers, heat exchangers, and sensors
- Durability studies and accelerated aging test methods
- Systems analysis and analytical capability



#### **RD&D Activities**

- The overall strategy of the HFCIT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation using close collaboration with industry that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps determine the performance and cost targets that technologies must meet to achieve goals of the HFCIT Program, as well as specific project objectives determined by peer review.
- DOE's HFCIT Program is carried out by national laboratories, universities, and the private sector, including cost-shared industry-led efforts; and CRADA collaborations between industry and the labs.

### **Recent Progress**

- Reduced the high-volume cost of automotive fuel cells from \$275/kW (2002) to \$200/kW (2004) using innovative processes developed by national laboratories and fuel cell developers for depositing platinum catalyst
- Achieved 54% efficiency in a stationary fuel cell stack assembly – on target to meet overall system electrical efficiency go/no-go target of 40% in 2010
- 5 kW stationary fuel cell system stack assembly efficiency is on track to meet overall system efficiency target of 32% in FY05
- Achieved long-term, 8X mass specific activity improvement of low Pt-content (Pt-Pd BNL) cathode catalysts
- Demonstrated a bipolar plate manufacturing process (at 20 parts per hour) that produces plates with target properties and acceptable performance

### **Commercialization and Deployment Activities**

- Major industrial companies are pursuing R&D in PEM fuel cells with a mid-term (5-10 years) time frame for deployment of these technologies for both stationary and vehicular applications. These companies include General Motors, Ford, Daimler-Chrysler, Toyota, Honda, United Technology Corporation Fuel Cells, Xcellsis, and Ballard.

## 2.2.6 HYDROGEN INFRASTRUCTURE SAFETY

### Technology Description

Similar to other commodities used as fuels in today's energy and transportation systems, hydrogen is classified as a hazardous material. Direct transport and storage of hydrogen can be achieved via pipelines, compressed gas storage vessels/cylinders, cryogenic vessels, as a hydride, or contained in a nanostructured material. Other commodities, including natural gas and methanol, also can be used as hydrogen carriers that are later reformed. Extensive hydrogen infrastructure is already in place to meet the transport needs of the petrochemical, fertilizer, electronics, and food industries. The approach to safely expand the hydrogen infrastructure is expected to build on current delivery approaches. Federal agencies are working to test and refine existing hydrogen technologies in compliance with Federal standards while developing new technologies that can improve hydrogen distribution, as well as reduce or eliminate leaks or other risks. Codes and standards must be adopted that support the safe, commercialization and integration of these technologies into the existing transportation and energy infrastructures of the United States.

### System Concepts and Representative Technologies

- There are currently three primary methods of hydrogen transport and storage: pipeline, vehicular commodity transport via tube-trailer/pressure vessels and cryogenic vessels, and stationary/fixed storage and fueling infrastructure.
- Within the United States, each of the three primary methods of hydrogen transport and storage is governed by a different set of regulations established by The U.S. Department of Transportation (DOT)/Pipeline and Hazardous Materials Safety Administration (PHMSA) and local and state fire marshals.
- The current system for transporting natural gas and hydrogen provides a reasonable foundation and model for expanding the hydrogen infrastructure. However, the current paradigm, with the exception of motor fuels and natural gas, is for hazardous materials (HAZMAT) transport to divert or restrict the transport of these materials into urban areas and through tunnels and other vulnerable transportation infrastructure.
- Current technologies include: small diameter hydrogen pipelines; DOT-approved pressure vessels and cylinders; DOT-approved cryogenic vessels; and, for stationary applications, pressure vessels complying with the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code.
- New technologies developed or being proposed include very high-pressure (13,000-15,000 psi), all-composite pressure vessels meeting both DOT and ASME requirements; advanced pipeline materials that reduce and/or catalyze permeated or leaked hydrogen; hydrides; below-ground cryogenic vessels; and nanostructured materials.
- These new technologies may be additions to or replace current transportation infrastructure, or may be integrated into the existing infrastructure.

### Technology Status/Applications

- Hydrogen has been transported and stored within the United States safely, securely, and reliably, for several decades using the current conventional (under 4,500 psi) technologies.
- New technologies to increase the efficiency and reduce the cost of hydrogen transport, such as advanced carbon composite cylinders and storage, are being adapted. New technologies are being reviewed and evaluated within the framework of the appropriate and necessary Federal regulations and other codes and standards.
- Other technologies, such as carbon nanotubes and advanced pipeline materials, are still in an early research and development (R&D) phase and are not ready for commercialization.
- The DOT/ Pipeline and Hazardous Materials Safety Administration (PHMSA) is currently reviewing applications for exemption for several technologies, including hydrides and high-pressure composite cylinder mobile fuelers, and is working with industry and the Department of Energy (DOE) to help guide safe and successful development and deployment of these technologies.

### Current Research, Development, and Demonstration

### RD&D Goals

- Work within the Federal government to develop, test, and approve new hydrogen storage and monitoring technologies.



- Conduct a thorough and comprehensive transportation and storage hydrogen infrastructure assessment to address capacity, safety, security, reliability, operations, and environmental compliance evaluating scenarios for near-term and long-term development and implementation of hydrogen infrastructure including a risk analysis for each technology and application.
- Investigate future systems that offer improved safety, security, reliability, and functionality vs. the current transportation and storage systems.

**RD&D Challenges**

- Gain a fundamental understanding of fatigue and failure modes of hydrogen materials including advanced composites and other storage media.
- Establish effective monitoring, inspection, and recertification technologies and procedures for hydrogen transport and storage.
- Adapt aging infrastructure to accommodate new demands.
- Educate and train operators, regulators, and users effectively.

**RD&D Activities**

- The overall strategy of the HFCIT Program is to conduct a comprehensive and balanced program that includes mid- and long-term research and development of hydrogen production, storage, and utilization technologies; integrated systems and technology validation using close collaboration with industry that develops, demonstrates, and deploys critical technologies emerging from research and development; and an analysis element that helps determine the performance and cost targets that technologies must meet to achieve goals of the HFCIT Program, as well as specific project objectives determined by peer review.
- DOE’s HFCIT Program is carried out by national laboratories, universities, and the private sector, including cost-shared industry-led efforts; d CRADA collaborations between industry and the labs.

**Recent Progress**

- To address the key barrier of perceived safety, the DOE initiated a successful effort to have the International Code Council (ICC) form a special committee to develop provisions specific to hydrogen for incorporation into its model building, fire, and fuel gas codes, which the ICC will publish for adoption by local jurisdictions throughout the United States. The ICC model codes will incorporate standards for hydrogen components and equipment being developed by leading organizations, such as the Society of Automotive Engineers and the International Standards Organization.
- Six chapters of a planned 15 chapters on hydrogen materials have been published on-line detailing properties of hydrogen materials and embrittlement.
- Through a consensus workshop process, a path forward has been established to integrate risk assessment analysis into the codes and standards process.
- Progress is being made in the development and revision of consensus codes and standards. Numerous draft standards are currently under review and adoption process. Excellent progress has been made in establishing an international hydrogen fuel-quality specification.

**Commercialization and Deployment Activities**

- Through its regulatory authority, DOT supports deployment and demonstration of pipelines and vehicles.
- The Operating Administrations of DOT, specifically the Pipeline and Hazardous Materials Safety Administration (PHMSA) and the National Highway Traffic Safety Administration (NHTSA), are actively engaged in domestic and international consensus codes and standards development.
- DOT staff support DOE R&D activities and the activities and committees of the various consensus codes- and standards-setting organizations.
- DOT staff continues to work with the National Association of State Fire Marshals to educate and train personnel and to promote safe handling and storage practices.