The U.S. Department of Energy Program on Hydrogen Production

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Clean forms of energy are needed to support sustainable global economic growth while mitigating greenhouse gas emissions and impacts on air quality. To address these challenges, the U.S. President’s National Energy Policy and the U.S. Department of Energy’s (DOE’s) Strategic Plan call for expanding the development of diverse domestic energy supplies. Working with industry, the Department developed a national vision for moving toward a hydrogen economy—a solution that holds the potential to provide sustainable clean, safe, secure, affordable, and reliable energy. DOE has examined and organized its hydrogen activities in pursuit of this national vision. This includes the development of fossil and renewable sources, as well as nuclear technologies capable of economically producing large quantities of hydrogen.

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I. Introduction

Clean forms of energy are needed to support sustainable global economic growth while mitigating greenhouse gas emissions and impacts on air quality. To address these challenges, the U.S. President’s National Energy Policy and the U.S. Department of Energy’s (DOE’s) Strategic Plan call for expanding the development of diverse domestic energy supplies. Working with industry, the Department developed a national vision for moving toward a hydrogen economy—a solution that holds the potential to provide sustainable clean, safe, secure, affordable, and reliable energy. In the hydrogen economy, hydrogen will be available for all of the economy’s end-use needs, including transportation, power generation, and portable power systems.

To realize this vision, the U.S. must develop and demonstrate advanced technologies for hydrogen production, delivery, storage, conversion, and applications. Toward this end, the DOE has worked with public and private organizations to develop a National Hydrogen Energy Technology Roadmap. The Roadmap identifies the technological research, development, and demonstration steps required to make a successful transition to a hydrogen economy.

One of the advantages of hydrogen is that it can utilize a variety of feedstocks and a variety of production technologies. Feedstock options include fossil resources such as coal, and natural gas, and renewable resources such as biomass and water. Production technologies include thermochemical, biological, electrolytic and photolytic processes. Energy needed for these processes can be supplied through fossil, renewable, or nuclear sources.

Hydrogen can be produced in large central facilities and distributed to its point of use or it can be produced in a distributed manner in small volumes at the point of use such as a refueling station or stationary power facility. In the shorter term, distributed production will play an important role in initiating the use of hydrogen due to its lower capital investment. In the longer term, it is likely that centralized production will be more cost effective, but distributed production will still play a role.

Utilization of nuclear and renewable technologies inherently addresses greenhouse gas emission directly. The use of fossil fuels requires the development of carbon dioxide sequestration technology to enable a hydrogen economy that also addresses climate change concerns.

Ultimately, a spectrum of feedstocks and technologies for hydrogen production will be necessary to address energy security and climate change concerns. The DOE Hydrogen Program will address multiple feedstock and technology
options to provide effective and efficient hydrogen production for the short term and the long term. The U. S. DOE Hydrogen Program is contained within the Offices of Nuclear Energy, Fossil Energy, and Energy Efficiency and Renewable Energy that are now working together synergistically to accomplish the overall program goals. There is a focus on distributed production to meet shorter term needs most cost effectively. To meet longer term needs, there is significant effort to provide competitive renewable feedstocks and energy sources, to develop centralized production from coal with carbon sequestration, and to develop high temperature processes using advanced nuclear reactors.

II. An Integrated Program

In his 2003 State of the Union speech, President Bush proposed a $1.2 billion research and development (R&D) activity to develop hydrogen powered vehicles and the production, storage, and delivery infrastructure to fuel them. This research is being pursued “so that the first car driven by a child born today could be powered by hydrogen, and pollution free.” To accomplish this task, various governmental organizations as well as various elements of the Department of Energy will be required to work together toward the common goal.

Two documents developed in cooperation with industry form the basis for the Department’s hydrogen activities; the National Vision of America’s Transition to a Hydrogen Economy and the National Hydrogen Energy Roadmap. The first states that “Hydrogen is America’s clean energy choice. Hydrogen is flexible, affordable, safe, domestically produced, used in all sectors of the economy, and in all regions of the country.” Building upon this vision, the National Hydrogen Energy Roadmap identifies the obstacles to achieving the vision and recommends areas of research and development to overcome those obstacles.

III. The Role of Nuclear Energy

The DOE recognizes that nuclear energy has a significant contribution to make toward a future hydrogen economy. As an emission-free, dense, economical source of electricity, nuclear energy can produce hydrogen using electrolytic processes in the near-term. This method allows the hydrogen to be generated at the point of use, which will be essential until significant infrastructure is developed. However, electrolysis is capital intensive for large production volumes, and the Department sees great opportunity in producing hydrogen using nuclear energy to thermochemically split water.

These thermochemical processes could use low cost, high temperature heat from advanced nuclear reactors and chemical cycles to dissociate water into its elemental constituents – hydrogen and oxygen. There are over 100 different thermochemical water splitting chemical cycles for hydrogen production that have been identified over the last 40 years. These processes incorporate several chemical reaction steps and require heat at temperatures of 100°C to 2000°C depending on the process. Since nuclear energy systems can be designed to supply high temperatures without atmospheric emissions, they are a very attractive complement to these hydrogen production methods and can achieve zero or near-zero net emissions. Although there are many such methods, only a handful are attractive technologically and/or economically. Advanced reactor designs being developed through the Department’s Generation IV Nuclear Power Systems Initiative (Gen IV), specifically the Very-High-Temperature Reactor (VHTR), are capable of extremely high temperatures, creating favorable economics. These technologies are still quite immature and will require significant research and development to reach commercial maturity.

Currently, two thermochemical cycles appear most promising, the Sulfur-Iodide (S-I) cycle and the Calcium-Bromine (Ca-Br) cycle. The S-I cycle has the highest quoted efficiency (about 52%) and requires temperatures in excess of 800°C, but has potential to provide low-cost hydrogen. The Ca-Br cycle requires lower temperatures, but has a predicted efficiency of only around 40-45%. Though the Ca-Br cycle is conceptually much simpler, it requires significant development. Research for both cycles is being funded by DOE as part of the Nuclear Energy Research Initiative (NERI) and is being evaluated in parallel for use with Gen IV reactors.

![Sulfur-Iodine Thermochemical Water-Splitting Cycle](image)

The S-I cycle involves three chemical reactions, two endothermic and one exothermic. Because all of the catalysts are recycled, the process results in a net chemical reaction of

\[ H_2O \rightarrow H_2 + \frac{1}{2} O_2 \]

as shown in Fig. 1. The primary reaction, or Bunsen reaction, converts iodine (I), water (H$_2$O), and sulfur dioxide

![Figure 1. Simplified diagram of Sulfur-Iodine (S-I) thermochemical cycle.](image)
(SO₂) into hydrogen iodide (HI) and sulfuric acid (H₂SO₄) while releasing heat at 125°C. The two products are then decomposed in parallel to release hydrogen and oxygen, respectively, while the remaining iodine and SO₂ is returned to the Bunsen reaction. The decomposition steps require significant temperatures to complete, 400°C for HI and >800°C for H₂SO₄, which can be provided by Gen IV reactors. As shown in Fig. 2, higher temperatures in the H₂SO₄ decomposition yield higher efficiencies. These higher temperatures also place higher demands on component materials, especially in the heat exchangers.

While the Ca-Br cycle operates at lower temperatures, significant materials issues are still present. The most common version of the Ca-Br cycle, the UT-3 process, is named for the University of Tokyo where the majority of the R&D was conducted. The UT-3 version of the cycle consists of four solid-gas chemical reaction steps. High temperature steam is passed through beds of CaBr₂ and FeBr₂ sequentially to produce hydrogen and HBr with some water being left unreacted. After separating the hydrogen from the stream, the remaining two products are passed through the final two steps to produce only oxygen and water. When the catalysts in the first two reaction steps are depleted, the reaction beds are moved to the end of the process (final two steps) to be regenerated. This method of periodically reversing the process flow is called a batch process. This is a less desirable method for large scale chemical processes than a continual process, such as the S-I cycle, but Argonne National Laboratory is working on methods to make the process more attractive. As it currently exists, the UT-3 cycle has significant materials issues, including development of effective supports for the solid catalysts used in the reaction beds and accounting for the changing chemical structure of the catalysts themselves.

In light of these R&D challenges, the Office of Nuclear Energy, Science and Technology (NE) has created a new initiative to begin in fiscal year (FY) 2004 with the goal of developing and demonstrating the ability of nuclear energy to economically produce hydrogen on a commercial scale by 2015. A Nuclear Hydrogen R&D Plan is currently being developed under the Gen IV program which will define the scope and schedule of the R&D to be conducted within the new initiative.

IV. Conclusion
Production issues are clearly not the only barriers to a hydrogen economy, and R&D in this area makes up only a portion of the Department of Energy’s Hydrogen Program. The program is also dedicating a large amount of resources toward issues associated with delivery, storage, conversions, and applications which will need to be resolved in parallel with production issues in order to make the national vision of a hydrogen economy a reality. The development of a portfolio of hydrogen production technologies, including nuclear energy technologies, is vital to strengthen the United States’ energy, economic, and national security.

References