Large Scale Hydrogen Production Using Nuclear Energy

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Outline

- Our Energy Future and the Hydrogen Economy
- How much hydrogen will be needed?
- How will it be produced?
- The role of nuclear energy
About our Energy Future

- World energy needs are growing rapidly
- There is a finite supply of oil and gas
- Alternative energy supplies need to be developed soon
- Environmental concerns are increasing
- America needs energy security & diversity
  - Petroleum imports will exceed 75% by 2025

WE NEED A SUSTAINABLE ENERGY SYSTEM
The Changing View of Our Energy Supply

Alexander Karsner, Asst. Secretary for DOE Energy Efficiency and Renewable Energy*

“I am motivated by these principles…

- We are a nation at war.
- Our earth is warming.
- Carbon emissions and greenhouse gases are impacting air quality and the environment.
- America is addicted to oil.”

Solutions....Will Require New Approaches and Innovation

Our world needs more energy
Growing World Energy Demand

- Rapid Energy Growth in Developing Economies
- China now is No. 2 Oil Importer (passing Japan)
- Growth Rate in Energy Use since 1980:
  - U.S. = 1.2% per year
  - China = 4.0% per year
  - India = 5.5% per year

Note: U.S. = 100 Quad
Oil and Gas are the Major Energy Sources

<table>
<thead>
<tr>
<th>History</th>
<th>Projections</th>
</tr>
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<tbody>
<tr>
<td>Oil</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>Coal</td>
<td>Renewables</td>
</tr>
<tr>
<td>Nuclear</td>
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</tbody>
</table>

Source: DOE/EIA IEO-2006
World Oil Production Predicted to Peak Before Mid-Century

Annual Production Scenarios with 2 Percent Growth Rates and Different Resource Levels (Decline R/P = 10)

USGS Estimates of Ultimate Recovery

<table>
<thead>
<tr>
<th>Probability</th>
<th>Ultimate Recovery</th>
<th>Billion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (95%)</td>
<td></td>
<td>2,248</td>
</tr>
<tr>
<td>Mean (expected value)</td>
<td></td>
<td>3,003</td>
</tr>
<tr>
<td>High (5%)</td>
<td></td>
<td>3,896</td>
</tr>
</tbody>
</table>

Note: U.S. volumes were added to the USGS foreign volumes to obtain world totals.

Source: DOE EIA & USGS
National Security demands Energy Security

"We have a serious problem. America is addicted to oil, which is often imported from unstable parts of the world."

President Bush
2006 State of the Union Address
January 31, 2006

Daryl Cagle, MSNBC website
What are our Options to Replace Oil?

- **Coal and Heavy Hydrocarbons**
  - Large resource base, including tar sands, oil shale
  - Large environmental signature
  - Global warming concerns

- **Renewable Energy Sources**
  - Biomass, Hydro, Wind, Solar
  - May only be partial solution (at least near term)

- **Nuclear Fission**
  - Worldwide renaissance in progress
  - No new U.S. reactors ordered since 1970’s

- **Nuclear Fusion** – long-term
A National Commitment to Hydrogen Technology

“Tonight I'm proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles... With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free.”

President Bush, January 28, 2003, State-of-the-Union Address
What is a Hydrogen Economy?

- Broad-based use of hydrogen as a fuel
  - *Energy carrier* analogous to electricity
  - Produced from variety of primary energy sources
  - Can serve all sectors of the economy: transportation, power, industry, buildings and residential
  - Replaces oil and natural gas as the preferred end-use fuel
  - Makes renewable and nuclear energy “portable”
    - can address transportation needs
Hydrogen as an Energy Carrier

- **Advantages**
  - Inexhaustible
  - Clean
  - Universally Available to All Countries

- **Major Challenges**
  - Reduce cost (10x) and increase durability (3x) of fuel cell power units; develop mass production
  - Reduce size, weight and cost of hydrogen storage
  - **Develop national hydrogen infrastructure**
    - Hydrogen production from sustainable sources
    - Large-scale transmission and distribution
    - Widespread refueling capabilities
A Hydrogen Economy will require massive amounts of hydrogen

- **Current industrial hydrogen use**
  - 10 million tons per year = 40 GW(th)
  - >90% used in oil refineries and ammonia plants
  - 5% of all U.S. natural gas usage is for hydrogen production

- **Projected hydrogen use for all light-duty vehicles in 2050***
  - 110 million tons hydrogen per year = 450 GW(th)
  - 11-fold increase over current industrial use
  - Same energy content as current avg. electrical demand (450 GWe)

- **Total energy for hydrogen production could equal or exceed that for electrical power generation by mid-century**

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*National Academies of Science, 2005.*
Hydrogen Production Options

- Hydrocarbons from fossil fuels
  - Current method for 98% of hydrogen production
  - Serious environmental and supply concerns

- Biomass
  - New hydrocarbons produced from solar energy
  - Large land area requirements; limited capacity

- Water-Splitting
  - Clean and sustainable
  - Needs large energy input to break H-O bonds
  - Requires cost effective, clean primary energy at large scale
Hydrogen can be made from a variety of domestic energy resources:

- Biomass
- Renewable Energy
  - Hydro
  - Wind
  - Solar
  - Geothermal
- Nuclear
- Oil
- Coal
- Natural Gas
- Heavy HC

With Carbon Sequestration

HIGH EFFICIENCY & RELIABILITY

ZERO/NEAR ZERO EMISSIONS

Transportation

Distributed Generation

Source: U.S. DOE
One View of a Nuclear Hydrogen Future

Centralized Nuclear Hydrogen Production Plant

Modular Helium Reactor

Thermochemical Process

$H_2O \rightarrow H_2 + \frac{1}{2} O_2$

Heat

Water

Time of Day/Month

$H_2$ Storage

High Capacity $H_2$ Pipeline

$H_2$

Industrial $H_2$ Users

Hydrogen Fueled Future

Distributed Power

Transport Fuel
Nuclear Energy and Hydrogen

“Within the scope of today’s technology, nuclear fission is the only viable, clean source of large quantities of energy.”

-Dr. Geoffrey Ballard
Founder, Ballard Power
(Fuel cell pioneer)

NOTE: A 1 GWe nuclear power plant requires 1 m³ of fuel per year and produces no carbon emissions. An equivalent fossil plant requires 4 million tons of coal (a train over 400 miles long) and produces 9 million tons of CO₂ per year.
Nuclear energy can help provide the hydrogen by several routes

- **Electric power generation** 🌍 Water Electrolysis
  - Proven technology; can use existing reactor type
  - Low overall efficiency ~24% (LWR), ~36% (Hi T Reactors)

- **Electricity + Heat** 🌍 High temperature steam electrolysis
  - Need both electricity generation and high temperature process heat
  - Efficiencies up to ~ 50%
  - Developing technologies (based on solid oxide fuel cells)

- **High temperature heat** 🌍 Thermochemical water-splitting
  - Uses advanced high temperature nuclear reactors
  - A set of chemical reactions that use heat to decompose water
  - Net plant efficiencies of up to ~55%, avoid cost of electricity generation
  - Developing technology
Advanced reactors are necessary for high temperature operation

Helium Gas-Cooled Reactor
- Modular Design
- Underground silo installation
- Capable of high temp operation (1000 °C)
- Refractory-coated fuel
- Passive safety
- Attractive economics

Source: General Atomics

TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

PARTICLES  COMPACTS  FUEL ELEMENTS
Hydrogen plant leverages reactor designs for power production

- Modular (600 MWth) reactors installed underground
- Passive safety eliminates need for containment structure
- Refractory fuel and gas-cooling permit high temperature operation -- 900-1000°C
- H2 plant requires replacement of power generation system with intermediate heat exchanger
- Secondary Helium loop used to transfer heat to hydrogen plant

Source: General Atomics
Nuclear Hydrogen Production Plant

- Reactor plant is combined with a water-splitting chemical plant
- All chemicals are recycled
- Only water and nuclear fuel are consumed
- Produces hydrogen and oxygen
- Highest thermal efficiency from nuclear heat to hydrogen
- Plant sizes from 200 to 800 tons per day of hydrogen (300 – 1200 MWth)

Courtesy of General Atomics
Thermochemical water-splitting

- Series of coupled chemical reactions
- Water consumption only; all intermediates regenerated
- Thermal input only (pure cycles) or thermal & electric input (hybrid cycles)
- Extensively studied in 1970s
- Over 3000 potential cycles have been suggested with 115 cycles reported in literature
- Thermodynamics dictate high temperature (>800°C)
- Potential for high plant thermal efficiency maximizing conversion of nuclear energy into hydrogen
Hybrid Sulfur (HyS) Process

Inputs:
- Water
- Heat
- Electricity

Outputs:
- Hydrogen
- Oxygen
- Waste Heat

- Simplest thermochemical cycle
- Requires heat (80%) and electricity (20%)
- Common high temperature acid decomposition step
Hybrid Sulfur (HyS) Process

- Simple, all fluids, two-step hybrid process
- Chemistry involves only S-O-H species
- Developed by Westinghouse Electric in 1970’s
- Closed-loop 120 lph bench-scale demonstrated in 1978
- Key development issues
  - Sulfuric acid decomposition (common with SI Cycle)
  - Optimization of flowsheet and SO$_2$/O$_2$ separation
  - Development and scale-up of SO2 electrolyzer
HyS Electrolyzer Concept

- Modification of water electrolysis process
- Uses sulfur dioxide to lower cell voltage by >75%
- Produces sulfuric acid that is sent to high temp section
- Design approach leverages R&D on PEM fuel cells
- Proof-of-concept achieved by SRNL in 2005
SO2-depolarized Electrolyzer Test Facility
Technology is still in early stages

- Major design challenges due to corrosive chemicals, impurities, reactant separation, high temperature heat exchange, and high capital costs
- High chemical-to-hydrogen weight ratios lead to large material flows and equipment sizes
- Currently in lab-scale development stage
  - Scale-up to MW-scale pilot plant in 3-5 years
- DOE plans to demonstrate full-size nuclear reactor combined with hydrogen plant in 2017
Delivered NuH2 is Competitive with Natural Gas Reforming

Breakeven Price for NG vs. NuH2 for Industrial H2 User

NG price real escalation = 2% per year

May 07
Summary and Conclusions

- World needs to convert to a sustainable energy system
- Hydrogen could replace oil and gas as a major energy carrier
- A hydrogen economy will need massive energy inputs
- Water-splitting is a preferred source of hydrogen
- Nuclear energy can produce large amounts of hydrogen at high efficiency with no greenhouse gases
- First nuclear hydrogen plant could be operating within ten years
THANK YOU