Technical Aspects of Clean Hydrogen Production

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Charles E. Taylor, Leader Methane Hydrates Research Group
National Energy Technology Laboratory
**Clean Coal Fuels Technology Lines**

- **Transportation Fuels and Chemicals**
  - **Coal Fuels**
  - **Hydrogen Production, storage and utilization**
  - **By 2010, hydrogen from coal can be produced for $30/bbl oil equivalent**

- **Advanced Fuels Research**
  - **C1 Chemistry**
  - **Improved synthesis gas conversion**
  - **By 2010, technology base enables coal liquid fuels to be produced at $30/bbl oil equivalent via coproduction w/ power**

- **Solid Fuels and Feedstocks**
  - **Coal-Derived Carbon Materials Separations**
  - **Premium Carbon Products/Coal Fines Recovery**
  - **By 2010, separation technologies permit higher coal recovery at less cost; high value carbon products enter the market**

**Key Milestones**
Hydrogen Production Options

Sources of Hydrogen

- Fossil Fuels with Sequestration
- Water
- Biomass

Sources of Heat to Drive Reaction

- Nuclear Power
- Renewables

The U.S. uses 14MM BPD of oil for transportation.

14MM BPD = 220MM TPY of H2 at current efficiencies.

Increasing annual coal production by 33% (330MM tons) would provide 50MMTPY of H2.

50MM TPY of H2 = 50% of our current transportation requirements at Freedom Car efficiencies.

Biomass photo: NREL, Calvert Cliffs Nuclear Plant
Hydrogen Production...How important is Coal?

The National Academy of Engineering recently completed a year long study of: “The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs”

Key Findings...General and those specific to coal:

- Hydrogen could fundamentally transform the U.S. energy system; therefore a robust, ongoing hydrogen program is important

- Fossil Fuels will be one of the principal sources of hydrogen for the hydrogen economy...but carbon capture and storage technologies will be required

- The U.S. has vast coal resources...hydrogen from coal can be inexpensive...and...coal must be a significant component of R&D aimed at making very large amounts of hydrogen.
Introduction

- The U.S. has a 250-year supply of coal at present annual use

- A small number of chemical plants use coal to produce hydrogen via partial oxidation

- Eastman Chemical gasifies coal to produce methanol for chemical manufacturing; methanol could also be used as a near-term source of hydrogen....now fueling Georgetown University fuel cell buses.

However -

- At present, no facilities based on modern coal gasification have been constructed that produce both hydrogen and power....the lowest cost path for producing hydrogen
Hydrogen From Coal: Goal

Facilitate the transition to a sustainable hydrogen economy through the use of coal, our largest domestic fossil resource

Objectives

• Production: Central Pathway
  --- By 2015, demonstrate a 60% efficient, zero emissions, coal-fueled hydrogen and power co-production facility that reduces the cost of hydrogen by 25% compared to current coal-based technology

• Production: Hydrocarbon Pathway
  --- By 2010, complete tests and evaluations of most promising hydrogen-rich, coal-derived liquids for reforming applications

• Storage
  --- By 2015, work with other DOE Offices to develop safe, affordable technology capable of storing 9 wt. % hydrogen

• Utilization
  --- By 2010, complete tests & evaluations of H₂/natural gas mixtures in modified and advanced internal combustion engines
Key Components: Hydrogen from Coal

- R&D Areas & Technical Hurdles
  - **Production**: H₂ separation; liquid fuels development
    - S-poisoning; catalyst-reactor, catalyst/wax separation
  - **Storage**
    - H₂/CH₄ mixtures, materials/processes for high wt.% H₂ storage
  - **Utilization**: H₂/natural gas combustion in ICEs
    - Performance and emissions control
  - **Process Engineering**: Intensification
    - Combine processes to increase efficiency/reduce capital cost
Hydrogen from Coal Program Roadmap

Central Production
- Advanced gas separation technology including membranes tolerant to trace contaminants identified
- Complete tests of sulfur-tolerant membranes and design of separation modules (CCPI)

Liquids Production
- Determine optimum liquids and reforming parameters; initiate advanced liquids production research
- Complete engineering designs and tests of advanced reforming and syngas processes

Infrastructure
- Complete lab tests of hydrogen storage …carbon and/or metal organic – based
- Complete bench tests and design of prototype hydrogen storage module

Utilization
- Perform exploratory research on use of H2/nat’l gas mixtures in ICEs
- Complete tests of H2/nat’l gas mixtures in conventional and advanced ICEs)

* Incorporates technology being developed under the complementary Advanced Gasification and Sequestration for carbon dioxide capture and storage programs

Complete Commercial Scale Demonstrations*

FreedomCAR and other Applications

NETL

2005 2010 2015
History of Gasification

- Used during World War II to convert coal into transportation fuels (Fischer – Tropsch)
- Used extensively in the last 50+ years to convert coal and heavy oil into hydrogen – for the production of ammonia/urea fertilizer
- Chemical industry (1960’s)
- Refinery industry (1980’s)
- Global power industry (Today)
Coal Gasification Can “Polygenerate” Many Products

Coal

- **Power**
  - Electricity
  - Steam

- **Fuels**
  - Fischer-Tropsch Diesel
    - Naphtha
    - Methanol
    - Dimethyl Ether **AND**
  - Hydrogen

- **Chemicals**
  - Waxes
  - Olefins
  - Acetates and many
  - Others
Gasification Basics

(Courtesy of Eastman Chemical)

**Products:**
- CO (Carbon Monoxide)
- H₂ (Hydrogen)

**By-products:**
- H₂S (Hydrogen Sulfide)
- CO₂ (Carbon Dioxide)
- Slag (Minerals from coal)

**Extreme Conditions:**
- Up to 1,000 psig or more
- Nominal 2,600°F (1400°C)
- Corrosive slag and H₂S gas
Integrated Gasification Combined Cycle (IGCC) Configuration

(Courtesy of Eastman Chemical)
Major Gasification Milestone

1842  Baltimore Electric Town Gas
1887  Lurgi Gasification Patent
1910  Coal Gasification Common in U.S. / Europe for Town Gas
1940  Gasification of Nature Gas for Hydrogen in the Chemical Industry (Ammonia)
1950  Gasification of Coal for Fischer-Tropsch (F-T) Liquids (Sasol-Sasolburg)
1960  Coal Tested as Fuel for Gas Turbines (Direct Firing)
1970’s IGCC Studies by U.S. DOE
1970  Gasification of Oil for Hydrogen in the Refining Industry
1983  Gasification of Coal to Chemicals Plant (Eastman Chemical)
1984  First Coal IGCC Demonstration (Coolwater Plant)
1990’s First Non-Recourse Project Financed Oil IGCC Projects (Italy)
1993  First Natural Gas Gasification F-T Project (Shell Bintulu)
1994  NUON/Demkolec’s 253 MWe Buggenum Plant Begins Operation
1995  PSI Wabash, Indiana Coal IGCC Begins Operation (DOE CCT IV)
1996  Tampa Electric Polk Coal IGCC Begins Operation (DOE CCT III)
1997  First Oil Hydrogen/IGCC Plant Begin Operations (Shell Pernis)
1998  ELCOGAS 298 MWe Puertollano Plant
2003  WMPI IGCC “Polygeneration” Projected Selected (CCPI I)
Cumulative Worldwide Gasification Capacity and Growth

MWth Syngas

Source: SFA Pacific Gasification Database - 2001
Comparison of Emissions Between IGCC and Other Coal-Fired Technologies

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>SO2 (lb/MWh)</th>
<th>NOx (lb/MWh)</th>
<th>PM10 (lb/MWh)</th>
<th>CO2 (10E-3 lb/MWh)</th>
<th>Total Solids, (10E-2 lb/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Plant (without SCR)</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>AFBC Plant (with SNCR)</td>
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<tr>
<td>PFBC Plant (without SNCR)</td>
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<tr>
<td>PC-Fired Plant with FGD &amp; SCR</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>

Legend:
- Red: SO2 (lb/MWh)
- Green: NOx (lb/MWh)
- Blue: PM10 (lb/MWh)
- Orange: CO2 (10E-3 lb/MWh)
- Grey: Total Solids, (10E-2 lb/MWh)
New Coal Marginally Competitive with Gas

- **Coal-Fired Power Plant**
  - Capital Cost: $1000 - $1200 / kW
  - Coal Price: $1.00 - $1.25 / MMBtu

- **Natural Gas CC**
  - Cost: $500 - $600 / kW

- **Cost of Electricity (Cents / kWh)**
  - Natural Gas Price ($ / MMBtu)

- **New Coal Marginally Competitive with Gas**
Factors Affecting Gasification

**Favorable**
- High NG prices
- Low quality feedstocks
- Feedstock flexibility
- Product flexibility/market matching
- Ultra-clean fuels
- Superior efficiency and environmental performance (requires monetization of benefits)
- Potential of more exacting emissions regulations

**Unfavorable**
- Low NG prices (commodity market uncertainties)
- Poor reliability
- Uncertainties in environmental regulations
- Lack of Investor confidence
- Real/perceived risks
- Project cost, size, and development time
- Large footprint
- Public perception of coal
Technology Hurdles

- Air Separation - Costly (12-15% of capital cost of IGCC) and inefficient (consumes 10% of gross plant power)

- Hydrogen Separation – Costly and inefficient for power applications

- Co-Production – Integration of power and fuels technologies

- CO₂ Sequestration – Ensure the gas does not escape from the reservoir its stored in
Mixed-Conducting Oxygen Separation Membranes

- Pressure driven operation
- Mixed ionic - electronic conduction, no external circuit
- Oxygen ion transport through oxide materials
- Infinite O₂ selectivity
- High temperature process - 900°C

N₂-Rich Air

1/2 O₂ + 2e⁻ → O⁻²

O⁻² → 1/2 O₂ + 2e⁻

O₂

Air

Oxygen Conducting Membranes
Example Scenario: Oxygen Separation

- Benefits of Oxygen Separation Membranes
  1. Lower capital cost than cryogenic oxygen systems
     - $20,000 → $13,000/tpd O₂ (35% decrease)¹
  2. Lower auxiliary power
     - 235 kWh/ton O₂ → 147 kWh/ton O₂ (37% decrease)¹

- Objectives
  Coal + 3/2 O₂ → CO₂ + H₂O
  1. Eliminate CO₂ capture system
  2. Simply remove H₂O and compress flue gas

Source: Air Products and Chemicals, Inc. 2002
Water Gas Shift - Hydrogen Separation
Membrane Reactor

CO + H₂O → CO₂ + H₂

catalyst

- Removal of hydrogen drives reaction to completion
- Carbon dioxide stream at high pressure, ready for sequestration
- Hydrogen available as a clean energy source
CO$_2$ Hydrate Formation for Gas Separation

- Forms clathrate by mixing CO$_2$ in fuel gas stream with chilled, recycled water stream

- Prior work by others predicted poor kinetics and problems with multi-phase flow
  - Results contradict slow kinetics theory – hydrate formation occurs readily with nucleation
  - Multi-phase flow problems will be managed with proper flow velocities and temperature control
Characteristics of a Gasification Process

(Courtesy of ChevronTexaco)

FEEDS
Alternatives:
- Asphalt
- Coal
- Heavy Oil
- Petroleum Coke
- Orimulsion
- Natural Gas
- Wastes
- Clean Fuels

GASIFICATION
Oxygen
Gasifier

GAS CLEANUP
Syngas
Sulfur Removal
Gas & Steam Turbines
Combined Cycle Power Block

END PRODUCTS
Electricity
Steam

Byproducts:
- Solids (ash)
- Sulfur

Marketable Byproducts:

Alternatives:
- Hydrogen
- Ammonia
- Chemicals
- Methanol

Source: ChevronTexaco
Gasification
Carbon Capture and Sequestration
Geologic Sequestration Options

- Deep Saline Formations
- Deep Coal Seams
- Enhanced Oil Recovery Fields
Geologic Sequestration Highlights
(1 Million TPY CO$_2$, ~ 100 MW Coal Power Plant)

\textbf{Weyburn CO$_2$ EOR Project}
- Pan Canadian Resources
- 200-mile CO$_2$ pipeline from Dakota Gasification Plant
- 130M barrels oil over 20-year project
- $28M

\textbf{Sleipner North Sea Project}
- Statoil
- Currently monitoring CO$_2$ migration
- $80M "incremental cost"
- $35/\text{ton CO}_2\text{ tax}
Sequestration R&D

- **Barrier Issues**
  - Health, safety and environmental risks
  - Permanence and large scale verification
  - Capacity evaluation
  - Infrastructure
  - Uncertain regulatory frameworks
  - Protocols for identifying amenable storage sites

- **Pathways**
  - Depleting oil reservoirs
  - Unmineable coal seams
  - Saline formations
  - Enhanced terrestrial uptake
  - Ocean fertilization and injection
  - Regional Partnerships
In Summary

• **Goal:** By 2015, a 60 percent efficient, zero emissions, coal-fueled hydrogen and power co-production facility is operational.

• **Benefits:**
  - Energy security
  - Early source of hydrogen for fuel cell vehicles
  - Reduced emissions of pollutants and GHGs
Visit Our NETL Website
www.netl.doe.gov

Visit Our OCES Website
www.netl.doe.gov/coalpower/index.html
Thank You

For Information on the Hydrogen from Coal Activity:

John Winslow
Technology Manager, Coal Fuels
NETL
412-386-6072
john.winslow@netl.doe.gov

Thank you very much for your time; I’m sorry I could not be with you in person today.