Ammonia as a Transportation Fuel IV

San Francisco

October 15-16, 2007

Norm Olson – Iowa Energy Center

www.energy.iastate.edu
Meeting Objectives

- Discuss Pro’s and Con’s of Ammonia as a Transportation Fuel
- Provide Facts to Help Enlighten Perspectives
- Report Progress
- Determine Next Steps
Oil Experts See Supply Crisis in Five Years

International Energy Agency

July 10, 2007
Energy Independence Goals

- Eliminate Petroleum Imports
- Provide a Bridge to Renewable Energy
- Protect the Environment
- Create U.S. Jobs/Improve Economy
- Eliminate Ammonia Imports
Background Information
The Fossil Fuel Era

- Traditional
  - Biomass
  - Wind
  - Water
  - Animals

- Fossil Fuels
  - Mechanical
    - Combustion
      - High temperature

- Renewables
  - Electric
    - Low temperature
    - Catalysts

% of total

Source: Ewald Breunesse, Shell Netherlands, 14th IAMA Annual World Conference, Montreux, June 14th 2004
Increasing dependence on oil imports

By Ahmad al-Quni

Sunday 10 August 2003, 12:43 Makka Time, 9:43 GMT

Per Capita Consumption (BPY): US - 28, China - 2

US imports over 60% of Petroleum (2004)

Iraq oil - the target for years By Ahmad Quni
Saudi Oil Exec: Only 18% of World's Crude Reserves Tapped

Wednesday, September 13, 2006

VIENNA, Austria — The world has tapped only 18 percent of the total global supply of crude, a leading Saudi oil executive said Wednesday, challenging the notion that supplies are petering out. Abdallah S. Jum'ah, president and CEO of the state-owned Saudi Arabian Oil Co., known better as Aramco, said the world has the potential of 4.5 trillion barrels in reserves — enough to power the globe at current levels of consumption for another 140 years.
World Crude Oil Reserves, Jan 2000

1,016.8 Billion Barrels
5897 Quads
OPEC Share = 78%

Source: Oil and Gas Journal, from the EIA website on International Petroleum Consumption

* = Member of OPEC

Saudi Arabia* 26%
Iran* 9%
Iraq* 11%
Kuwait* 9%
United Arab Emirates* 10%
Qatar* 0%
Libya* 3%
Algeria* 1%
Nigeria* 2%
Other Far East 2%
Canada 0%
Mexico 3%
China 2%
U.S. 2%
Othr So America 1%
Norway 1%
U.K.+ other Eur 1%
Kazakhstan + Other former USSR 1%
Russia 5%
Othr Middle East 1%

OPEC Shares as a Percentage of Total World Reserves:

Saudi Arabia 26%
Iran 9%
Iraq 11%
Kuwait 9%
United Arab Emirates 10%
Qatar 0%
Libya 3%
Algeria 1%
Nigeria 2%
Other Far East 2%
Canada 0%
Mexico 3%
China 2%
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Othr So America 1%
Norway 1%
U.K.+ other Eur 1%
Kazakhstan + Other former USSR 1%
Russia 5%
Othr Middle East 1%

OPEC Share = 78%
Coal Reserves
World Recoverable Coal Reserves - January 1999

- 25% United States
- 23% Soviet Union
- 12% China
- 9% Australia
- 7% India
- 7% Germany
- 6% South Africa
- 2% Serbia
- 2% Poland
- 7% Other

World Total: 1089 Billion Short Tons
19554 Quads

World Crude Oil Reserves in 2000 - 78% OPEC
US Coal

Average Weekly Coal Commodity Spot Prices
Trading Week Ended July 2, 2004

Coal Commodities by Region:
- Central Appalachia (CAP): Big Sandy/Kanawha 12,500 Btu, 1.2 lb SO2/mmBtu
- Northern Appalachia: Pittsburgh Seam 13,000 Btu, <3.0 lb SO2/mmBtu
- Illinois Basin: 11,800 Btu, 5.0 lb SO2/mmBtu
- Powder River Basin: 8,800 Btu, 0.8 lb SO2/mmBtu
- Uinta Basin in Colo.: 11,700 Btu, 0.8 lb SO2/mmBtu

*Prior to January 11, 2002, EIA averaged 12-month “forward” spot prices for several coal specifications; after that date, coal prices shown are for a relatively high-Btu coal selected in each region, for delivery in the “prompt” quarter. The “prompt quarter” is the next calendar quarter, with quarters shifting forward after the 15th of the month preceding each quarter’s end.

Source: with permission, selected from listed prices in Platts Coal Outlook, “Weekly Price Survey.”
Hydrogen Sources

- Renewables
- Fossil Fuels
- Nuclear
Renewable Energy Options

- Wind
- Solar
- Hydro
- OTEC
- Biomass
- Others
**Enough Biomass?**

<table>
<thead>
<tr>
<th>2002 Consumption</th>
<th>Quads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td>38.11</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>23.37</td>
</tr>
<tr>
<td>Coal</td>
<td>22.18</td>
</tr>
<tr>
<td>Nuclear</td>
<td>8.15</td>
</tr>
<tr>
<td>Renewable</td>
<td>5.25</td>
</tr>
<tr>
<td>Corn potential (including stalk, 10 bil. bu.)</td>
<td>8.40</td>
</tr>
</tbody>
</table>
## Solar, Wind, Biomass

<table>
<thead>
<tr>
<th>Technology</th>
<th>Converter Efficiency</th>
<th>Capacity Factor</th>
<th>Packing</th>
<th>Land per Year for: km²/GW</th>
<th>Land per Year for: m²/GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat-Plate PV</td>
<td>10-20%</td>
<td>20%</td>
<td>25-75%</td>
<td>10-50</td>
<td>5000 - 25,000</td>
</tr>
<tr>
<td>Wind</td>
<td>Low to 20%</td>
<td>20%</td>
<td>2-5%</td>
<td>100</td>
<td>140,000</td>
</tr>
<tr>
<td>Biomass</td>
<td>0.1% total</td>
<td></td>
<td>High</td>
<td>1000</td>
<td>500,000</td>
</tr>
</tbody>
</table>

Source:

http://www.nrel.gov/docs/fy04osti/35097.pdf
Fossil Fuel Hydrogen Sources

- Petroleum
- Natural Gas
- Coal
Dakota Gasification

Over 20 years of producing natural gas, ammonia and other valuable chemicals from US coal.

Al Lukes - $4.50 Nat. Gas from new coal gasification plants.
China

- # new plants
- Chart of chemicals produced
Europe

The Homepage of the R&D Component of the European Commission Clean Coal Technology Programme

euro-cleancoalf.net
Chemistry

From Coal

C + H2O $\rightarrow$ CO + H2

CO + H2O $\rightarrow$ CO2 + H2

From Natural Gas

CH4 + H2O $\rightarrow$ CO + 3H2 (Steam Reforming)

CO + H2O $\rightarrow$ CO2 + H2

Ammonia

N2 + 3H2 $\rightarrow$ 2NH3
Performance
The Perfect Transportation Fuel

• Can be produced from any raw energy source (i.e. wind, solar, biomass, coal, nuclear, hydro etc.)

• Is cost effective

• Has significant storage and delivery systems already in place

• Is environmentally friendly

• Can be used in any prime mover (i.e. diesel engines, fuel cells, SI engines, gas turbines, etc.)
Hydrogen Carriers

- Liquefied Hydrogen (H₂) 100%
- Compressed Hydrogen (H₂) 100%
- Natural Gas (CH₄) 25.0%
- Ammonia (NH₃) 17.6%
- Ethanol (C₂H₆O) 13.0%
- Methanol (CH₄O) 12.5%
Energy densities (LHV) for fuels in liquid state

[Bar graph showing energy density (MJ/liter) for various fuels, with a highlighted range for hydrogen density.]
# Freedom Car Targets w/ 2005 NH3 Comparison

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spec. Energy</td>
<td>kWh/kg</td>
<td>1.5</td>
<td>2</td>
<td>3</td>
<td>3.0</td>
</tr>
<tr>
<td>Energy Density</td>
<td>kWh/L</td>
<td>1.2</td>
<td>1.5</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Storage Cost</td>
<td>$/kWh</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>2.1</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>$/gal. Gas equiv</td>
<td>3</td>
<td>1.5</td>
<td>1.5</td>
<td>1.7*</td>
</tr>
</tbody>
</table>

*$280/ton ammonia
## Fuel Costs

**June 2003 Chemical Market Reporter* $/MMBtu**

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost Details</th>
<th>Price ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>$200/metric ton*</td>
<td>$10.01</td>
</tr>
<tr>
<td>Gasoline</td>
<td>$1.20/gallon</td>
<td>$10.52</td>
</tr>
<tr>
<td>Methanol</td>
<td>$0.79/gallon*</td>
<td>$13.68</td>
</tr>
<tr>
<td>Ammonia</td>
<td>$270/short ton</td>
<td>$14.86</td>
</tr>
<tr>
<td>Ethanol</td>
<td>$1.25/gallon* ($2.70, 9/05)</td>
<td>$16.44</td>
</tr>
<tr>
<td>Gasoline</td>
<td>$2.00/gallon</td>
<td>$17.54</td>
</tr>
<tr>
<td>Wind</td>
<td>$0.035/kwh x 2 (electrolyzer)</td>
<td>$20.51</td>
</tr>
<tr>
<td>Gasoline</td>
<td>$2.50/gallon</td>
<td>$21.92</td>
</tr>
<tr>
<td>Ethanol</td>
<td>$2.70/gallon (9/05)</td>
<td>$35.51</td>
</tr>
</tbody>
</table>
Gasoline Costs – March 2005

What we pay for in a gallon of Regular Gasoline (March 2005)
Retail Price: $2.08/gallon

- Taxes: 21%
- Distribution / Marketing: 6%
- Refining: 19%
- Crude Oil: 54%

Source: Energy Information Administration, 2005
Future Compatibility

Hydrogen + Nitrogen

Ammonia

Storage & Delivery – Pipeline, Barge, Truck, Rail

Stationary Power  Fertilizer  Transportation
Economic Impacts

Current (2003) Imports: ~ 13 million bpd
= $114 billion/year @ $24/bbl, $228 billion @ $48/bbl

2003 Gasoline Consumption – 8,756,000 bbl/day
15.3 x 10\(^{15}\) Btu/year = 850 million ton/year ammonia

1250 new plants @ 650,000 ton/year each
$562 billion investment @ $450 million/plant

375,000 new jobs

$5 billion annual new tax revenue/year (employees only)
Delivery Infrastructure
Typical New Infrastructure

Filling Stations – fuel tanks,

Chicago Stations (20)

Delivery (cold or pressurized?)

Natural Gas/Petroleum Pipeline retrofit?

One fuel (+pilot) simplifies fuel infrastructure.

Simplified refineries and formulations
California Hydrogen Stations

[Map of California showing locations of hydrogen stations]

http://www.fuelcellpartnership.org/fuel-vehl_map_print.html
Over 800 retail ammonia (the “Other Hydrogen”) outlets currently exist in Iowa.
Ammonia Pipeline
Ammonia Storage & Transport
Anhydrous ammonia expands into a gas as it is injected into the soil where it rapidly combines with soil moisture.
End Use Applications

• Spark-Ignition Internal-Combustion Engines (w/ethanol)
• Diesel Engines (w/biodiesel)
• Direct Ammonia Fuel Cells
• Gas Turbines
• Gas Burners
Health And Safety

“Safety assessment of ammonia as a transportation fuel”, Nijs Jan Duijm, Frank Markert, Jette Lundtang Paulsen, Riso National Laboratory, Denmark, February 2005

<table>
<thead>
<tr>
<th>Chemical</th>
<th>#Incidents</th>
<th>Fatalities</th>
<th>Rel. Freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>3936</td>
<td>82</td>
<td>5.3x</td>
</tr>
<tr>
<td>LPG</td>
<td>915</td>
<td>9</td>
<td>2.5x</td>
</tr>
<tr>
<td>Anhyd. Ammonia</td>
<td>1016</td>
<td>4</td>
<td>--</td>
</tr>
</tbody>
</table>
Scapegoat?

Ammonia \( \text{NH}_3 \)

Ephedrine and Pseudoephedrine \( \text{C}_{10}\text{H}_{15}\text{NO} \)

Methamphetamine \( \text{C}_{10}\text{H}_{15}\text{N} \)

\( \text{VOC}'s + \text{NOx} + \text{O}_2 + \text{Sunlight} = \text{ozone} = \text{smog}^+ \)

\( \text{NOx} + \text{H}_2\text{O} + \text{ammonia} = \text{ammonium nitrate} = \text{smog}^- \)

If the NOx doesn’t form ammonium nitrate it goes to ozone (worse)

Fossil fuels (the source of NOx ) are the problem, not ammonia

Ammonia is actually used to clean up NOx emissions at coal plants
## Ammonia Toxicity Ratings

<table>
<thead>
<tr>
<th>Corresponding NFPA Index</th>
<th>Toxicity Rating</th>
<th>Descriptive Term</th>
<th>LD&lt;sub&gt;50&lt;/sub&gt; (wt/kg) single oral dose rates</th>
<th>LC&lt;sub&gt;50&lt;/sub&gt; (ppm) 4 hours inhalation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1</td>
<td>Extremely Toxic</td>
<td>&lt; 1 mg</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>Highly Toxic</td>
<td>1-50 mg</td>
<td>10-100</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>Moderately Toxic</td>
<td>50-500 mg</td>
<td>100-1000</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>Slightly Toxic</td>
<td>500-5000 mg</td>
<td>1000-10,000</td>
</tr>
<tr>
<td>0</td>
<td>5</td>
<td>Practically non-toxic</td>
<td>500-15,000 mg</td>
<td>10,000-100,000</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Relatively Harmless</td>
<td>&gt; 15,000 mg</td>
<td>&gt; 100,000</td>
</tr>
</tbody>
</table>

Ammonia - NH<sub>3</sub>  
LD<sub>50</sub> = 350  
LC<sub>50</sub> = 2000

The NFPA rating for ammonia is 3 taking into account the physical stress of emergency people. The actual NFPA health ratings based solely on the actual LD<sub>50</sub> and LC<sub>50</sub> numbers would be 2 and 1 respectively. Since we are most concerned with inhalation risks, the NFPA rating based on actual test data for ammonia should be 1 or “slightly toxic”.
NFPA Classifications

<table>
<thead>
<tr>
<th>Substance</th>
<th>Health</th>
<th>Flammability</th>
<th>Reactivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>3 😟</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Gasoline</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Benzene, Ethyl benzene</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>MTBE</td>
<td>1 😟</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Natural gas, Methane</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>LPG</td>
<td>1</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Methanol, Ethanol ?, Toluene, Hexane</td>
<td>2</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

NFPA ratings span from 0 to 4 (0 = no special hazards, 4 = severe hazards). Based on actual test data, the NFPA Health rating for ammonia should be 1 (as an inhalation risk). It is interesting to note that gasoline gets a Health Rating of 1, yet many of its significant components have Health Ratings of 2 and 3.
Progress

• Irrigation pump demonstration with SI engine
• Over 50% efficiency demonstrated in an IC engine
• Direct ammonia fuel cell
• Wind to ammonia demonstration funded
• 95% ammonia, 5% diesel, full power, LOWER NOx!!!
• New ammonia synthesis technologies
Summary

- Ammonia Meets Most 2015 Freedom Car Targets Today
- Ammonia Has a Very Extensive, Worldwide Delivery and Storage Infrastructure Already in Place
- Only H2 and NH3 Have No Tailpipe Greenhouse Gas Emissions
- Only H2 and NH3 Can be Made From Electricity and Water (+air for NH3)
- Ammonia From Fossil Fuels Now
- Ammonia From Renewables in the Near Future
- Diesel and Spark-Ignition IC Engines Now
- Fuel Cells in the Future
- Ammonia Looks Very Good Now and in the Future
- Ammonia is Safer Than Gasoline and Hydrogen