NH$_3$ – The **Optimal** Alternative Fuel

ARPA-E REFUEL Kickoff Meeting
August 17-18, 2017
Denver, Colorado

Norm Olson
President - NH3 Fuel Association
NH₃ – Optimal Fuel, Versatile Chemical

Fuel

Energy Storage

Fertilizer

Refrigerant
NH3 FA and AIChE Meeting

Become a member of the NH3 FA and attend the AIChE Annual Meeting at a significant discount (see details at link below).

https://nh3fuelassociation.org/join-us/


NH3 Energy+ Topical Conference. 40 presentations!
Recent Developments

Netherlands Conference (~150 attendees) - Europe’s First! Shell, Yara, Ammonia Casale, IEA, Siemens, Proton Ventures, etc. 2017

Japan Program 2015-2018
Siemens wind to NH3 project in Great Britain 2016-2017 (UMM 2008)
Global NH3 Fuel Federation 2016
IEA – white paper 2017
Ammonia Casale – 10 tpd unit announced 2017
Australia – 1st non-U.S. NH3 FA chapter 2017
ARPA-E DOE – 13 NH3 fuel related projects 2017
AIChE – 40 presentations 2017
ACS – first ever NH3 fuel session in 2017
Hydrofuel - Greg Vezina, 1981
And many more
NH3 Facts - Production

Source: Fertecon, CRU, PotashCorp. Last updated: Aug 31, 2014
NH3 Facts - Consumption

CF Expects Global Nitrogen Demand To Grow at 2 Percent per Year

Total Nitrogen Consumption 2000-2019
(Million Nutrient Tonnes)

- Industrial
  - 15-yr CAGR = 3.5%
- Agricultural
  - 15-yr CAGR = 1.9%

<table>
<thead>
<tr>
<th>Product</th>
<th>Percentage of 2015 Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>NITROGEN:</td>
<td></td>
</tr>
<tr>
<td>Explosives</td>
<td>16%</td>
</tr>
<tr>
<td>Urea: resins, amine</td>
<td>33%</td>
</tr>
<tr>
<td>Ammonia:</td>
<td></td>
</tr>
<tr>
<td>Caprolactam, Acrylonitrile, Polymers</td>
<td>51%</td>
</tr>
<tr>
<td>D.A. Ammonia</td>
<td>3%</td>
</tr>
<tr>
<td>AS</td>
<td>5%</td>
</tr>
<tr>
<td>UAN</td>
<td>6%</td>
</tr>
<tr>
<td>AGAN</td>
<td>8%</td>
</tr>
<tr>
<td>CAN Compound</td>
<td>21%</td>
</tr>
<tr>
<td>Urea</td>
<td>57%</td>
</tr>
</tbody>
</table>

Data Sources: Faratecan, IFA, AAPFCO, Fertilizer’s Europe, ANFAA Analysis: CF Industries
NH3 Production vs U.S. Gasoline Use


2016 World NH3 Production: 180 million tonne = ~80 Billion Gallon = ~40 Billion GGE

~3.5x
NH₃ Affordability

Similar to propane infrastructure costs
2nd most transported chemical in world
Over 3000 miles of NH₃ pipeline in U.S.
800 retail outlets in Iowa alone
1.3 times more hydrogen than liquid H₂ (by volume)
NH₃ Production Costs w/ Cap X

Natural Gas Represents More Than 75 Percent of US Producers' Costs
Natural gas is the most important feedstock in ammonia production and, depending on price, makes up 70-85 percent of the US cash cost of producing ammonia. Cap X: $1500/ton, 30 year amortization, ~$50/ton

Gasoline @ $3.50/gallon = $30/MMBtu

NH₃ $/MMBtu  GGE $
18  $2.10
15  $1.40
12  $1.00
9   $0.70
Ammonia Storage & Transport
1st Hydrogen Shipment? Not really.

“Australia and Japan prepare for world’s first bulk hydrogen shipment “
Zoe Reynolds | 11 January 2017
## NH3 vs Hydrogen Storage Costs

<table>
<thead>
<tr>
<th>Application</th>
<th>NH3 (250 psi)</th>
<th>CNG (3200 psi)</th>
<th>H2 (10k psi)</th>
<th>Cryo NH3 (-28 F)</th>
<th>Cryo H2 (-423 F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-board vehicle</td>
<td>$700</td>
<td>$1500</td>
<td>$6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filling station</td>
<td>$68,000²</td>
<td></td>
<td>$2,643,840³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large storage facility</td>
<td>$20 million⁴</td>
<td></td>
<td>$81.6 million³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹Phone conversation with John Coursen, Worthington Industries, February 17, 2017. Relative ~costs ~50 liter tank: LPG/NH3 - $700, CNG (3200 psi) - $1500, Hydrogen (10,000 psi) - $6000.

²1Phone conversation with Don Wallace, Trinity Containers. 18,000 gallon NH3 bullet tank - $68,000. @80% fill capacity = 14,400 gallon x 5lbs/gallon x 0.176 lbs H2/lb NH3 / 2.2 lbs/kg = 5760 kg = $11.81/kg H2.


⁴Rentech Press Release, January 12, 2012. Chilled NH3 20,000 ton = $20 million. 20k ton x 2000 x 0.176 /2.2 lbs/kg = 3.2 million kg. H2.
What Makes NH₃ Optimal?

- Affordability
- **Safety**
- Efficiency
- Environmental Performance
- Sustainability
- Production Flexibility
- End-Use Flexibility
- County Building
Safety

Numerous design choices – As safe as it needs to be.

Pressurized storage – safe enough to meet most stringent standards
Chilled storage – safer yet: -28 F NH₃, -265F LNG, -420F H₂
Chemical storage – Too safe? Amminex, ammonium carbonate (solids)
Ammonia’s Safety Reputation: Whence comest thou?

Bhopal, 1984, Union Carbide, Methylisocyanate release, 1000’s killed.

U.S. response:- EPCRA developed, 300 “extremely hazardous chemicals”. NFPA: 2 to 3 arbitrarily.

40 times more lethal. EV range 100 x 40 = 4000 miles
40 mpg x 40 = 1600 mpg
## Table 1: Toxicity Classes: Hodge and Sterner Scale (CCOHS)

<table>
<thead>
<tr>
<th>Corresponding NFPA Ratings (LC50)</th>
<th>Toxicity Rating</th>
<th>Commonly Used Term</th>
<th>Oral LD50 (Single dose to rats) mg/kg</th>
<th>Inhalation LC50 (Exposure of rats for 4 hours) ppm</th>
<th>Dermal LD50 (Single application to skin of rabbits) mg/kg</th>
<th>Probable Lethal Dose for Man</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (0-100)</td>
<td>1</td>
<td>Extremely Toxic</td>
<td>1 or less</td>
<td>10 or less</td>
<td>5 or less</td>
<td>1 grain (a taste, a drop)</td>
</tr>
<tr>
<td>3 (100-500)</td>
<td>2</td>
<td>Highly Toxic</td>
<td>1-50</td>
<td>10-100</td>
<td>5-43</td>
<td>4 ml (1 tsp)</td>
</tr>
<tr>
<td>2 (500-2500)</td>
<td>3</td>
<td>Moderately Toxic</td>
<td>50-500</td>
<td>100-1000</td>
<td>44-340</td>
<td>30 ml (1 fl. oz.)</td>
</tr>
<tr>
<td>1 (2500-20,000)</td>
<td>4</td>
<td>Slightly Toxic</td>
<td>500-5000</td>
<td>1000-10,000</td>
<td>350-2810</td>
<td>600 ml (1 pint)</td>
</tr>
<tr>
<td>0 (&gt;20,000)</td>
<td>5</td>
<td>Practically Non-toxic</td>
<td>5000-15,000</td>
<td>10,000-100,000</td>
<td>2820-22,590</td>
<td>1 litre (or 1 quart)</td>
</tr>
<tr>
<td>0 (&gt;20,000)</td>
<td>6</td>
<td>Relatively Harmless</td>
<td>15,000 or more</td>
<td>100,000</td>
<td>22,600 or more</td>
<td>1 litre (or 1 quart)</td>
</tr>
</tbody>
</table>

**Source:** Canadian Centre for Occupational Health and Safety (CCOHS). NFPA data addition by Norm Olson, NH3 FA.

LC50/4hour (ppm): NH3 - 2000; Chlorine – 146.5; Methyl Isocyanate – 5 (Source: Praxair, other)
Safety I

- NH3 is a common, naturally occurring chemical found in or used by nearly all animal life forms. It is not a carcinogen and is not a greenhouse gas. Its ozone depletion number is zero.
- NH3 is safer than propane and as safe as gasoline when used as a transportation fuel.
- “Safety assessment of NH3 as a transportation fuel”, Nijs Jan Duijm, Frank Markert, Jette Lundtang Paulsen, Riso National Laboratory, Denmark, February, 2005
Safety II

- NH3 plant operators – hydrogen vs NH3
- NH3 is classified by DOT as a non-flammable liquid and an inhalation hazard (not a poison)
- The degree of safety for NH3 Fuel is an engineering decision and does not require any technology miracles/breakthroughs (unlike hydrogen and electric vehicles).
- The challenge: Design an ASME tank and valve system that is fail safe. A rather trivial challenge.
NH₃ Refueling Station

NH₃: The Key to U.S. Energy Independence

12,000 Gal Chilled NH₃
What Makes NH₃ Optimal?

- Affordability
- Safety
- **Efficiency**
- Environmental Performance
- Sustainability
- Production Flexibility
- End-Use Flexibility
- County Building
## Production Energy Efficiency

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<th>Process</th>
<th>kWh/kg H2</th>
<th>%LHV</th>
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<tr>
<td>NH3 via Haber-Bosch</td>
<td>2.26(^1)</td>
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<td>700 bar H2 Refueling (880 bar)</td>
<td>2.85(^2)</td>
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<td>Liquid H2</td>
<td>10(^2)</td>
<td>30.1%</td>
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<tr>
<td>Liquid H2 (advanced)</td>
<td>7(^2)</td>
<td>21.1%</td>
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Efficiency in Engines

Octane, Octane, Octane

NH₃’s very high octane rating (>120) and high (tunable) resistance to detonation allow the use of extremely high compression ratios and therefore IC engines with the highest possible efficiencies.
NH$_3$ IC Engine Efficiency

Source: Van Blarigan, Sandia National Lab, 2001
Nissan SOFC Vehicle – 60% Eff.? 

https://www.youtube.com/watch?v=HF-eE8pRzMw
What Makes NH₃ Optimal?

- Affordability
- Safety
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- **Environmental Performance**
- Sustainability
- Production Flexibility
- End-Use Flexibility
- County Building
Cleaner Than Hydrogen?! 

No carbon  
NH₃ used to clean up NOₓ  
Zero measurable pollutants possible with IC engines  
Not a greenhouse gas  
Ozone depletion number of zero  
Not a known carcinogen  
Huge natural occurrence in the earth’s nitrogen cycle  
Natural mechanisms for spill remediation
What Makes NH$_3$ Optimal?

- Affordability
- Safety
- Efficiency
- Environmental Performance
- **Sustainability**
- Production Flexibility
- End-Use Flexibility
- County Building
Sustainability

As long as the sun continues to shine, the earth’s atmosphere contains significant amounts of nitrogen, there is some readily available source of hydrogen, and iron is available as a catalyst....

NH₃ will be sustainable on planet earth!
What Makes NH$_3$ Optimal?

- Affordability
- Safety
- Efficiency
- Environmental Performance
- Sustainability
- **Production Flexibility**
- End-Use Flexibility
- County Building
Production Flexibility

NH₃ can be produced using any and all primary energy sources including but not limited to .... Solar, natural gas, wind, nuclear, OTEC, coal, hydro, etc.

Scalability of NH₃ production plants is very good and could range from units as small as one ton per year to mega-ton production facilities.

Affordable NH₃ could be produced from (carbon free) natural gas now and from any renewable energy source (and water) in the near future.

Several promising new alternative NH₃ production technology alternatives are being developed (i.e. alternatives to Haber-Bosch)
Nuclear Synergism – Fusion?

- **Capacity**
  - +20 Nuclear Capacity
  - NH₃ Production
  - Peaking Units Required

- **Load**

- **Nuclear Capacity (Baseload)**

- **Time of Day**
What Makes NH₃ Optimal?

• Affordability
• Safety
• Efficiency
• Environmental Performance
• Sustainability
• Production Flexibility
• **End-Use Flexibility**
• County Building
End Use Flexibility

SI engines
CI engines – dual fuel now...high compression future
Fuels cells
Gas turbines
Burners

Optimizing prime movers for a single fuel has huge benefits. An engine designed to use both gasoline and ethanol severely compromises the efficiency potential of ethanol, another very-high octane fuel.
What Makes NH₃ Optimal?

- Affordability
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- Country Building
NH₃ fertilizer made from a fraction of the net increase in crop residue (e.g. corn stalks) due to the addition of NH₃ fertilizer, allows a transition from subsistence farming to income-producing farming. NH₃ fuel allows for locally produced transportation fuels and rural combined heat & power (CHP) units. NH₃ refrigerant allows for efficient and environmentally-friendly cold food and perishables storage.

Where another of our other favorite chemicals (H₂O) exists, one relatively simple refinery producing NH₃ can provide enhanced, sustainable food production; a versatile transportation fuel; distributed electrification via CHP units; long-term, efficient renewable energy storage; and efficient refrigeration systems. This provides an excellent base for local self-sufficiency and a greatly improved standard of living.

Petroleum refineries are very complex and require a very large scale.
Bio-Refinery
Renewable Energy: Stranded and Long-term Storage

A significant amount of renewable energy will either be stranded (i.e. produced remotely and converted to a form that can be transported long distances) or will need long-term storage. Chemical storage likely be used for these two applications. NH₃ will likely be the most cost-effective option for chemical storage.

Once renewable energy is stored as NH₃, it is more efficient and cost-effective to use the NH₃ as a liquid transportation fuel in FCV and/or ICEV than to convert it to electricity and deliver it through the grid to EV filling stations for use in EV’s.
Effective Energy Storage

Source: Hydrogenius Technologies. NH3 addition by NKO.
NH3 vs H2 vs Methylcyclohexane

700 bar Hydrogen - 0.03899 g/cm³ x 100% H2 = 0.03899
Liquid Hydrogen (-253 C)– 0.07099 g/cm³ x 100% H2 = 0.07099
Liquid Ammonia (NH₃, -33C) – 0.682 g/cm³ x 17.6% H2 = 0.12003
Methylcyclohexane (MCH) – 0.77 g/cm³ x 6.1% H2 = 0.04700

NH₃ dehydrogenation requires 31 kJ/mol H₂. Methylcyclohexane dehydrogenation requires 68 kJ/mol H₂, or ~ 2.2 times more energy per mole of hydrogen than for NH₃.

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Conclusion

NH$_3$: is clearly, the most affordable carbon-free fuel
is the most efficient fuel in an internal combustion engine
has optimal environmental performance
has production flexibility second to none
has excellent end-use flexibility (tunable fuel)
has tremendous business development opportunities
is the optimal choice for an alternative fuel

Many times “all of the above” or diversity is very beneficial – primary energy source
diversity, food diversity, locations to live, music

Some times selecting one, optimal choice (standardization) has huge benefits –
meanings of words, standard weights and measures, transportation/generation fuels.

Optimized engine/fuel cell/turbine cost/efficiency/emissions; optimized, non-redundant infrastructure; safety protocol optimization; optimized production effectiveness...

Prodigious business opportunity and tremendous world-wide benefits.
Top Technology Developments

Vaccines
Synthetic Ammonia Fertilizer (Haber-Bosch)
Personal Computer
Internet
NH₃ Energy?
NH₃ – The Optimal Alternative Fuel

Thank You!

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https://nh3fuelassociation.org/