NH3 – "THE OTHER HYDROGEN ™"

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1. Introduction

The environmental, national security and economic problems associated with U.S. dependence on imported petroleum are of primary concern to U.S. citizens. A cost effective, environmentally friendly, domestically produced alternative fuel would solve many of the most daunting problems facing the U.S. Taking a step back and defining the characteristics of an ideal alternative fuel is important to making optimized decisions and may, in fact, have a large role in determining the status of the United States of America's ranking as a world power.

In the search for an ideal fuel, the following criteria might be included:

1. Produced from any raw energy source (i.e. wind, solar, biomass, coal, nuclear, hydro etc.)
2. Cost effective
3. Significant and practical storage and delivery systems already in place
4. Environmentally friendly (No Carbon, Low Emissions)
5. The ability to be used in any prime mover (i.e. diesel engines, fuel cells, SI engines, gas turbines, etc.)
6. A proven, acceptable safety history
7. Sustainable
8. Produced in the U.S.

Hydrogen in its traditional forms (i.e. compressed and cryogenic) meets most of the criteria listed above but it can be argued that hydrogen in the form of anhydrous ammonia (NH3) is the single fuel that best meets the ideal fuel characteristics listed above. While traditional forms of hydrogen generally perform well in items 1 and 4-8, the cost effectiveness due to challenges in storing and delivering compressed and cryogenic hydrogen are huge barriers to near-term, wide-spread use of hydrogen in these traditional forms. Storing, delivering and using hydrogen in the form of NH3 provides an immediate solution to the most significant barrier to the hydrogen economy, a cost-effective delivery infrastructure. Just as pork has been trademarked as "the other white meat", NH3 has justifiably been trademarked as "the other hydrogen ™". Hydrogen and "the other hydrogen" both suffer from perceived safety issues, however, educating the public with facts and demonstrations will show that some hydrogen fuels can be used as safely as gasoline and safer than propane, a widely accepted vehicle fuel.

The details of how NH3 performs relative to the ideal fuel criteria will be addressed in the following sections. Hydrogen delivered as NH3 provides a compelling case for meeting the goals of the NHA and DOE at a dramatically accelerated pace.

2 Body

Production Flexibility

A huge benefit associated with a hypothetical "ideal fuel" would be the ability to produce this fuel from any and all primary energy sources. While some people are promoting wind energy as the solution to all of our problems, others are convinced that solar will eventually be our primary energy source of choice. Some think that the tremendous coal resource in the U.S. combined with new technologies to construct zero emission coal facilities with carbon dioxide sequestration is the most cost-effective near-term solution. Another group believes nuclear power is the answer, some promote biomass as the best choice, others ocean thermal energy and the list goes on… and on. A fuel that can be produced from any and all of these primary energy sources makes it impossible to make a wrong choice of primary energy sources. Any primary energy source or combination of primary energy sources chosen can be used to produce the "ideal fuel". Over time the primary energy sources of choice will change, but the ideal alternative fuel and, most importantly, the storage and delivery infrastructure associated with the ideal fuel would remain in place.

There is a very short list of alternative fuels which can be made from all primary energy sources: hydrogen. Hydrogen can be produced and stored as compressed hydrogen, cryogenic hydrogen and in many other forms, but the production, storage and use of hydrogen in the form of NH3 has a unique set of impressive benefits. Given the opportunity to examine these issues in depth, most people would conclude that it would be foolish to exclude wind, solar and other non-biomass renewable energy sources as potential contributors to the world's transportation fuel needs.

While the quest for making ethanol from cellulose is an ongoing challenge, producing NH3 with high energy yield from cellulose can be accomplished using commercially available technologies. More net energy per acre of corn is produced when making NH3 than can be produced making ethanol.

A 1.5 MW wind to ammonia demonstration is scheduled to begin operation at the University of Minnesota Morris in the spring of 2009. Ocean Thermal Energy (OTE) systems appear to have the potential to produce significant quantities of NH3 at competitive costs. It takes a relatively small amount of additional energy to produce NH3 once hydrogen has been produced via electrolysis or other means. Combining nitrogen from the atmosphere with hydrogen to produce NH3 using the Haber-Bosch process is an exothermic reaction.

NH3 can be produced from any renewable, fossil or nuclear energy source using the Haber-Bosch process and potentially from some new processes currently under development. Regardless of the path taken, nitrogen (78% of earth's atmosphere is nitrogen) from the atmosphere can be combined with hydrogen from any source to produce NH3.

Cost Effectiveness

The ideal fuel must be cost effective and not become an unaffordable luxury to the majority of the world's population. Energy costs must not inhibit reasonable economic development and industrial production. The cost of energy influences the cost of every product produced and delivered. The recent escalation of food prices (2008) was mistakenly blamed on corn ethanol. While the higher price of corn had some impact on higher food prices the real culprit was highly inflated oil prices which increase production costs, packaging costs, shipping costs, etc. High energy costs have a ripple effect throughout the entire economy and have a disproportionate negative effect on poorer countries where there is little or no disposable income. Energy costs need to become stable and reasonable in cost to help stabilize world economies and especially to help third world economies running optimally.

In 2003, before energy prices began their latest round of wild fluctuations, NH3 was priced at approximately $200 per metric ton at the Gulf of Mexico while wholesale gasoline was approximately $1.25 per gallon. This represents a cost of $10.01 and $10.96 per million Btu for NH3 and gasoline respectively. Recent (January 2009) NH3 delivered prices to Tampa according to a publication entitled, "The Market – Fertilizer News and Analysis, 31 December 2008" were $125 per tonne which is equivalent to a wholesale gasoline cost of approximately $0.71 per gallon. Due to an unusual set of circumstances NH3 was selling at a price as high as $800 per metric ton in 2008, in the same time frame when gasoline was selling for over $4 per gallon. In general, NH3 has been very cost competitive with gasoline as a transportation fuel over the past 20 years. As an additional point of reference, ethanol at March 2009 prices ($1.68 per gallon) is approximately equivalent to a wholesale gasoline cost of $2.50 per gallon. China, currently the world's largest producer of NH3, has proven that low cost NH3 can be produced via coal gasification.

The cost of NH3 fertilizer should actually decrease due to the use of NH3 as a fuel. This is due to the fact that NH3 fertilizer equipment is currently used for only a few weeks per year and NH3 used as a fuel would make use of this equipment throughout the entire year.

Infrastructure, Infrastructure, Infrastructure

The ideal fuel would make use of existing fuel delivery infrastructure. The storage and delivery infrastructure issue is one of the most challenging to deal with depending on the fuel or fuels chosen. Hydrogen may have the biggest hurdles to overcome in this area. Biodiesel may have the easiest path of integration with existing infrastructure; ethanol has significant infrastructure problems; propane and ammonia have storage and delivery infrastructure issues that are similar in nature. Hydrogen in the form of NH3 is annually in the top three chemicals in terms of volume transported worldwide. It is shipped by truck, rail, trans-oceanic ship and barge. An ammonia pipeline from the Gulf of Mexico to Minnesota and with branches to Ohio and Texas has served the NH3 industry for several decades. More importantly, since ammonia can be shipped and stored in mild steel pipelines, any natural gas or petroleum pipeline could be cost-effectively converted to carry NH3. Almost two million miles of natural gas pipeline in the U.S. could be converted to carry NH3, making NH3 fuel readily available to nearly every community in the U.S. A pipeline of a given size can deliver nearly 50% more energy when transporting liquid NH3 than if it is used to deliver compressed natural gas. A 50% increase in energy delivery capacity represents a huge cost savings and energy savings. Pressurized NH3 storage and delivery infrastructure is very similar in design and performance to propane (LPG) delivery infrastructure, because they are both compressed liquids at moderate pressure. The significant, proven, worldwide availability of propane fueled vehicles and furnaces, provides a familiar example of how ammonia fuel systems would appear physically.

A comparison of the production, storage and delivery of compressed hydrogen verses hydrogen in the form of NH3 provides some very revealing information. As can be seen in Figures 1 and 2 it is much more energy efficient and much lower cost to produce, store and deliver hydrogen as NH3 than as compressed and/or cryogenic hydrogen.

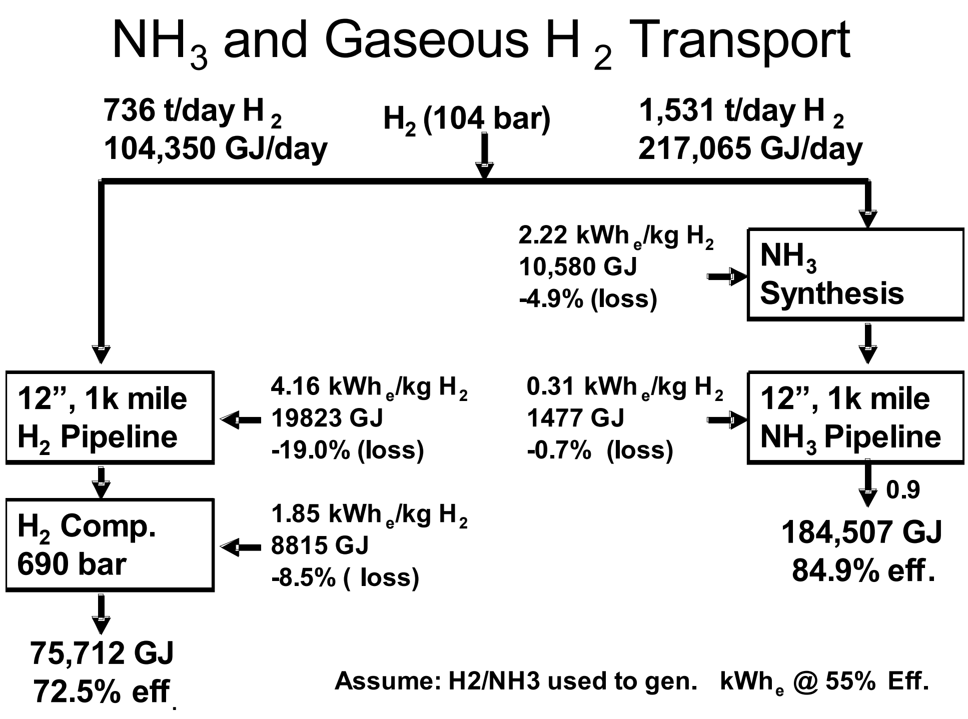

Figure1

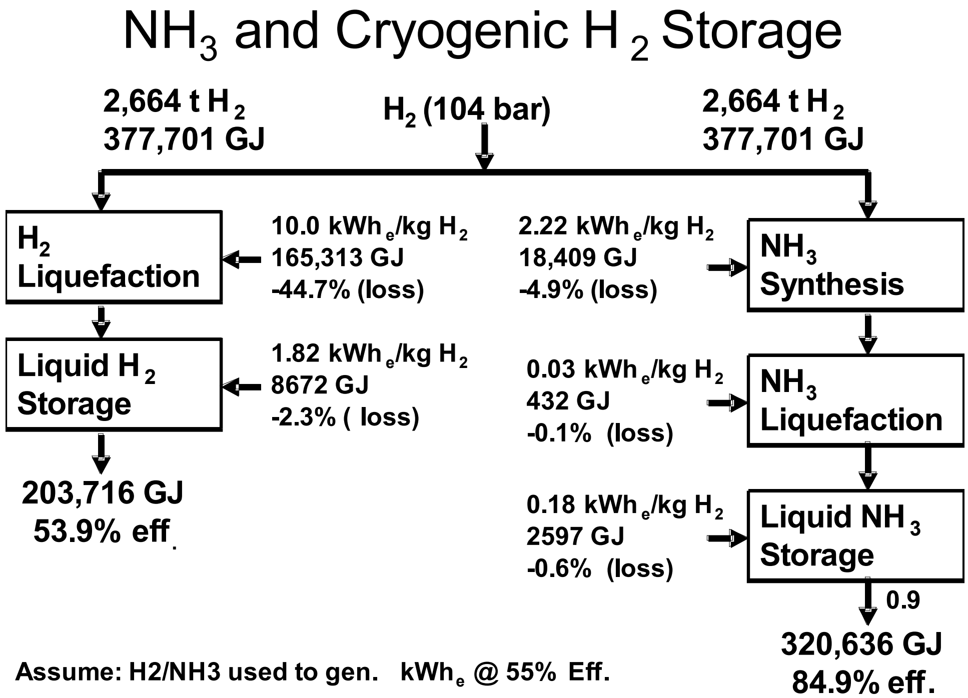

Figure 2

Environmentally Friendly

The ideal fuel would not produce any greenhouse gas emissions or air and water pollution of any type. Environmental issues are becoming increasingly important as global warming concerns become increasingly vocalized. The use of hydrogen as a fuel becomes the standard by which all other alternative fuels are measured. Biofuels, once considered to be CO2 neutral now been characterized by some as having more CO2 emissions than petroleum gasoline! This characterization is not accurate but it shows how this type of debate can take some surprising directions. When NH3 is used as a fuel in internal combustion engines with simple catalytic converters, only N2 (which is 78% of the air we breath) and water vapor are produced making NH3 as clean as hydrogen from an environmental standpoint. NH3 has an ozone depletion potential (ODP) of zero and a global warming potential (GWP) of zero. Environmentally speaking, hydrogen and "the other hydrogen ™" as NH3 has been called, are in a class by themselves.

Flexible End-Use (Used by Any Type of Prime Mover)

The ability to use one fuel in all types of combustion engines, gas turbines, burners and directly in efficient fuel cells is a tremendous advantage. Storage and delivery infrastructure would be greatly simplified, far fewer fuel formulations would be required and would be easier to produce to a given standard, refueling stations would be standardized and lower in cost, etc. NH3 is one of a very short list of fuels that can be used in nearly every type of engine and gas burner with only modest modifications. Relatively minor modifications allows efficient use of ammonia as a fuel in diesel engines; high-compression-ratio spark-ignition engines can produce astounding efficiencies of over 50% using NH3 fuel; direct ammonia fuel cells promise to be low-cost, robust and very efficient; NH3 is also a very suitable fuel for use in solid oxide fuel cell and gas turbines.

Direct ammonia fuel cells are under development at Natural Resources Canada and by Dr. Jason Ganley at Howard University. These medium-temperature (approximately 400 C) fuel cells promise to be low-cost (due to low-cost catalysts and packaging), highly efficient and very robust.

The Hydrogen Engine Center (HEC) and nh3car have both produced spark ignition engines that have demonstrated the use of NH3 fuel for hundreds of hours. The use of 95% NH3 combined with 5% diesel fuel has been successfully demonstrated at Iowa State University in a John Deere diesel engine. The diesel engine running with this fuel mix produced 110% of rated load at full load.

Gas burners can be equipped with in-line partial reformers to split approximately 5% of the NH3 into hydrogen. This mixture produces a robust, clean burning open flame.

One pipeline to a home could provide NH3 to furnaces/boilers, fuel cells, stationary generators and even vehicles. Due to the very mild enthalpy of reforming exhibited by NH3 it can easily be reformed to hydrogen for any application that would require hydrogen.

Safety

Hydrogen and NH3 have both had to deal with rational and irrational concerns regarding their safe use as a fuel. There are risks associated with the use of any fuel and every attempt must be made to keep the discussion in the rational, factual realm. In the U.S. Midwest, where NH3 has been routinely used in an acceptably safe fashion for decades, there is a healthy respect for the risks associated with the use of NH3 but its safe use has become routine. The U.S. stores, transports, and uses 15 – 20 million tons of NH3 or NH3-based fertilizers per year in the nation's heartland.

NH3 is a chemical commonly found in nature and consists of one atom of nitrogen and three atoms of hydrogen. It is a key intermediary in the naturally occurring nitrogen cycle and is essential in many biological processes. The great majority of ammonia in the environment comes from the natural breakdown of manure and dead plants and animals. Ammonia is one of the most abundant, naturally occurring gasses in our environment. Only three percent of the ammonia produced annually on this planet is man-made, synthetic ammonia, the remainder is produced by natural processes. On average, 17 grams of ammonia are emitted daily by every human via natural biological processes. Ammonia used as a fertilizer and refrigerant has an excellent, decades-long safety record.

Making ammonia "acceptably safe" from a statistical standpoint is an easily-solved engineering design issue. There are risks associated with the use of ammonia as a fuel however all fuels have inherent dangers associated with their use. NH3 is lighter than air and when released usually dissipates rapidly. NH3 is safer than propane and comparable to the safety of gasoline when used as a transportation fuel.

Two significant studies and a host of anecdotal evidence support the acceptably safe use of ammonia as a fuel. A report from Denmark in 2005 entitled, "Safety assessment of ammonia as a transportation fuel", Nijs Jan Duijm, Frank Markert, Jette Lundtang Paulsen, Riso National Laboratory, Denmark, February 2005 " concludes that NH3 would be as safe as the use of gasoline as a transportation fuel. A comparative quantitative risk assessment (CQRA) entitled "Comparative Quantitative Risk Assessment of Motor Gasoline, LPG and Anhydrous Ammonia as an Automotive Fuel" completed in March 2009 by Quest Consultants Inc., Norman, Oklahoma, shows NH3 to be comparable to gasoline and safer than propane when used as a transportation fuel. Figures 3 and 4 show graphical results of the Quest CQRA for truck transport of the three fuels and at a refueling station respectively.

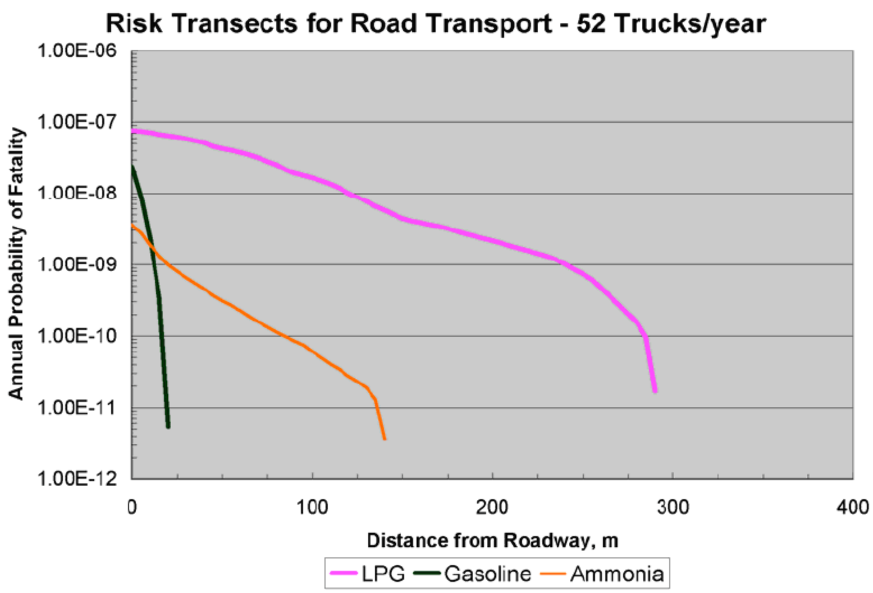

Figure 3

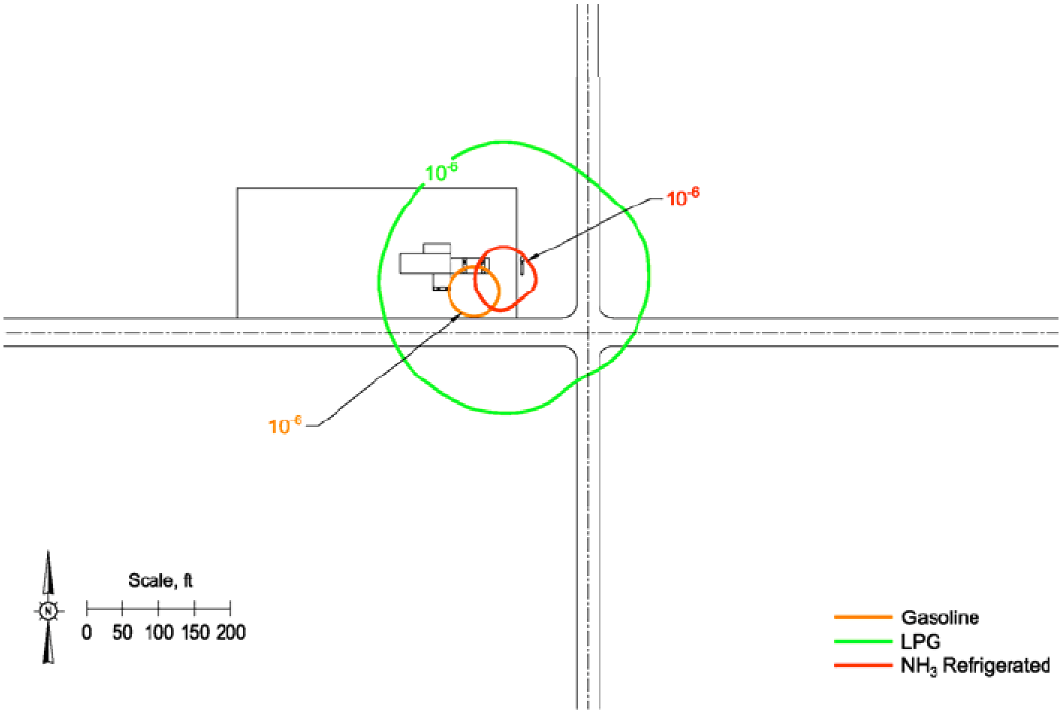

Figure 4

The summary from the Quest Consultants Inc. CQRA reads as follow, "In summary, the hazards and risks associated with the truck transport, storage, and dispensing of refrigerated anhydrous ammonia are similar to those of gasoline and LPG. The design and siting of the automotive fueling stations should result in public risk levels that are acceptable by international risk standards. Previous experience with hazardous material transportation systems of this nature and projects of this scale would indicate that the public risk levels associated with the use of gasoline, anhydrous ammonia, and LPG as an automotive fuel will be acceptable."

Other anecdotal evidence may be enlightening as well. Although commonly available world wide NH3 has not been used by terrorists to kill and injure people. Terrorists have commonly used gasoline, diesel fuel, chlorine and many other chemicals as weapons of terror. The inventor of the process developed in the early 1900's commonly used to produce NH3, Fritz Haber, was awarded a Nobel Prize for developing this technology that has provided fertilizer to help feed the world. Haber was also known as the "father of modern chemical warfare". He was obviously very familiar with NH3 and deployed numerous chemical weapons during World War I, but he did not use NH3.

Some concerns have been raised regarding the use of NH3 in the production of methamphetamine. A quick review of the chemical formulas for the cold medicines ephedrine and pseudo ephedrine compared to the chemical formula for methamphetamine provide very revealing information. There is no way to make methamphetamine without ephedrine and pseudo ephedrine, but there are several ways to make methamphetamine without NH3.

Ammonia	NH3
Ephedrine and Pseudo ephedrine	$C_{10}H_{15}NO$
Methamphetamine	$C_{10}H_{15}N$

Sustainable
NH3, like hydrogen can be made from all primary energy sources and therefore is as sustainable as the choice of primary energy source used. It takes approximately one gallon of water to make one gallon of NH3 when electrolysis is used to produce the hydrogen used to make NH3. For comparison it takes approximately 3 gallons of water to make one gallon of ethanol at modern dry mill plants. Water used to produce a gallon of gasoline is also substantially higher than that used to produce NH3

Born in the U.S.A.
The Pickens Plan, developed by T. Boone Pickens states that if the U.S. developed a plan to produce its energy domestically it would create a new U.S. industry worth $3 – 6 billion annually! This is a project that would not only provide hundreds of thousands of new jobs but would also eliminate the huge national security risks associated with U.S. dependence on foreign oil. It would help arrest the unpredictable high price-low price fluctuations associated with the uncertainties of petroleum oil making investment decisions more predictable and funding more easily obtained.

3 Conclusion

Hydrogen delivered in the form of NH3 has some compelling strengths and has the potential to make the hydrogen economy a reality in the near-term, at an affordable cost. NH3 will be safer than propane and at least as safe as gasoline when used as a transportation fuel. The environmental performance of NH3 is second only to hydrogen (and a close second at that) due to the fact that it has an ozone depletion potential (ODP) of zero and a global warming potential (GWP) of zero. Any NOx that may be formed during the combustion of NH3 can easily be converted to N_2 and H_2O. The huge advantages associated with the fact that ammonia is easy to store, can be produced from all renewable, fossil and nuclear energy sources and used in any type of combustion engine or burner puts NH3 in a class by itself. Extensive production, storage, and delivery infrastructure for NH3 is already in existence and the fact that existing natural gas pipelines could easily be converted to transport NH3 (with a 50% increase in energy carrying capacity) is a benefit that makes hydrogen delivered as NH3 the leading candidate for a near-term, cost-effective alternative fuel. NH3 fuel may be the key to U.S. energy independence in an environmentally beneficial manner.