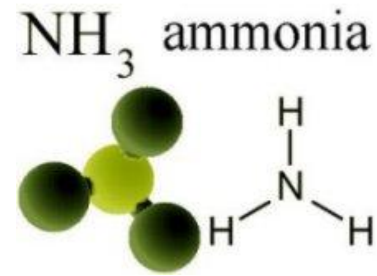
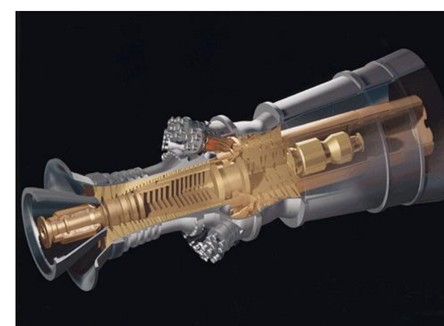
8th NH3 Conference



Selection of NH3 for Gas Turbine Use

Arif Karabeyoglu and Brian Evans

Space Propulsion Group Inc.
Sunnyvale CA



September 19, 2011

NH3 Conference - Portland

Statement of the Problem

Energy carrier/storage problem

- Fossil fuels have high energy densities which makes them a perfect medium for carrying and storing energy
- Energy carrying medium must have the properties
  - high in energy density
  - clean
  - safe
  - cost effective

Energy carrier/storage solution

- Hydrogen and batteries are proposed as solutions. Both have major shortcomings
- Solution is mode dependent
  - Transportation systems (automobile, rail, shipping and air travel)
  - Electric power generation
  - Residential/commercial heating

Concentrate on gas turbine power generation mode

Ammonia based fuels

SPG Advancing Propulsion & Energy

Why Ammonia?

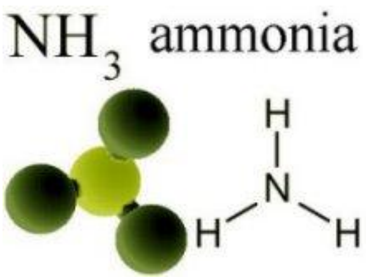
NH3 Conference - Portland

Opportunity – NH3 as Energy Carrying/Storing Medium

Green Fuel

As Fuel Source

- NH3 is a fuel source that contains no carbon
- When burned with air no green house gases are generated
- NH3 can also significantly reduce the Nox emissions
- NH3 is not a green house gas itself



NH3 Production

- Production process has to be considered to assess the environmental benefits of NH3
- Energy efficient, carbon free methods are possible in producing NH3

NH3 Transportation/Storage

- NH3 is a widely used commodity
- NH3 can be stored at ambient temperature
- NH3 can be transported effectively using pipelines, railroads, shipping and trucks

SPG Advancing Propulsion & Energy

NH3 Conference - Portland

Chemical Storage Media Comparison

	Process	Fuel Production Efficiency, %	CO_2 Emission* lb/mmBTU	Storage Pressure, psi
Ammonia	Haber-Bosch	60-65	0	200
Diesel	Fischer-Tropsch	67	165	14.7
Hydrogen (Gaseous)	Steam Forming	59	0	14.7 (not compressed)
CNG	Compression	88	110	3,000

* Point of use

- Natural gas is the feedstock for all fuels listed in the table
- Production of ammonia using the Haber-Bosch process is almost as efficient as the production of diesel fuel using Fischer-Tropsch process
- Only CO_2 emission free options listed on the table are ammonia and hydrogen. Ammonia is a better energy carrier due to its higher energy density, lower explosion hazard and better conversion efficiency

SPG Advancing Propulsion & Energy

Why Electricity Generation?

NH3 Conference - Portland

Transportation vs Electricity Generation

Due to its high hydrogen density, ammonia has been studied as transportation system fuel extensively

"DOE does not plan to fund R&D to improve ammonia fuel processing technologies for on-board use on **light weight vehicles** at the present time"
Ref: *Potential Roles of Ammonia in Hydrogen Economy*, *DOE Report, Feb 2006*.

The following are quoted as the main reasons
- Safety – toxicity
- Ammonia cracking issues: start up, efficiency, conversion rate
- Storage: Lack of light, compact and robust storage tanks

	Transportation	**Electricity Generation**
Safety	Very critical	Not as critical
Cracking	Cracking reactors heavy/expensive	Easily done
Storage tank weight	Critical	Not an issue
Storage tank robustness	Need to be "Indestructible"	Existing storage tanks are suitable
Distribution	Complicated	Relatively simple
Start up	Problematic	Not many start ups
Operational	Pumps operated by unprofessionals	Delivered/handled by professionals

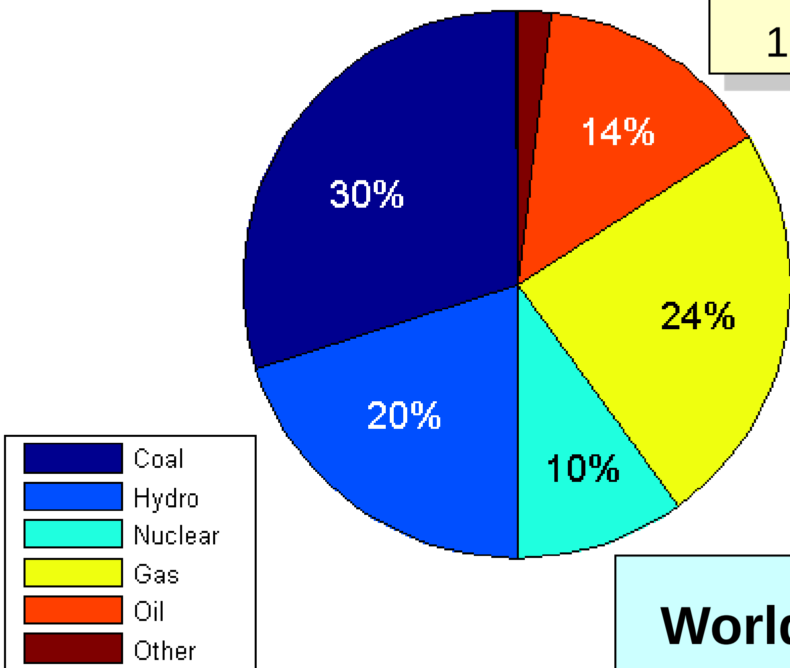
Major shortcomings of ammonia for transportation systems are NOT relevant to electricity generation

Why Gas Turbines?

NH3 Conference - Portland

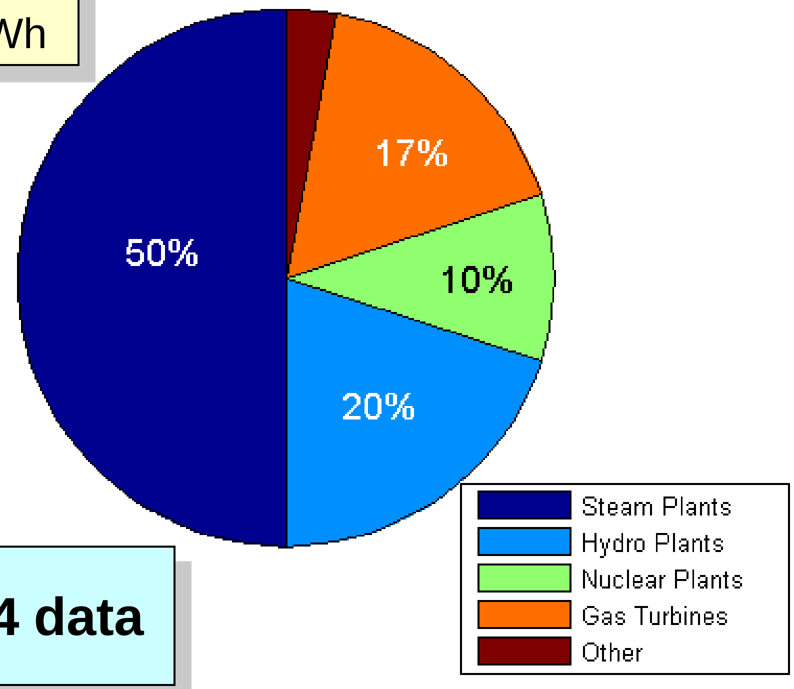
Electricity Generation Market

Fuels



Total Capacity
16,668 billion kWh

Technology



World Wide 2004 data

- Coal fired conventional steam plants still dominate energy generation market
- Energy generation by the gas fired gas turbines has been growing rapidly
- Oil fired plants can be converted to clean burning ammonia gas turbines

NH3 Conference - Portland

Gas Turbine Power Generation

Older plants are rapidly being displaced by gas turbine power generators

- Gas turbines supplied 15% of US power generation in 1998.
- Portion will be 39% by 2020.
- Of new demand 81% is for gas turbine power.
- Market is ~ $10 billion. About 700 to 800 new units sold per year.

Engine Types in Use

- Heavy duty gas turbines - centralized power production, 30 to 500 MW.
- Lightweight gas turbines - derived from aircraft engines, generally less than 60 MW.
- Micro gas turbines - distributed power, less than 5 MW

Why Gas Turbines?

- High efficiency - Up to 60% with steam co-generation.
- Low emissions - NOx < 10 ppm.
- Low installed cost - 25,000 hr maintenance interval.
- Multi-fuel capability - Natural gas (methane) is fuel of choice when available. Fuel transition while running

SPG Advancing Propulsion & Energy

NH3 Conference - Portland

Gas Turbine Power Generation – Role of Ammonia

Target Market 1 – Lightweight and Micro Gas Turbines

- Even with the current production technologies and excluding the CO_2 emission related issues ammonia is an economically viable option for
  - Oil fired light weight gas turbine systems
  - Oil fired micro gas turbines used for distributed power generation
- Note that since CO_2 sequestration is NOT feasible for these relatively small power generation units, ammonia has huge environmental advantages over fossil fuels.
- This market opportunity exists currently and does not require the development of new production/distribution/storage technologies for ammonia.

Target Market 2 – Heavy Duty Gas Cycles

- Most of these plants utilize natural gas. Thus within the current paradigm switching to ammonia is not economically viable.
- However since ammonia is a commodity that can be shipped cost effectively compared to natural gas, the production of ammonia in large production facilities at the natural gas source (where the natural gas is as low as the 1/10th the market value in the US*) using CO_2 sequestration would make ammonia a viable alternative to natural gas even for the heavy duty combined cycle power generation plants.

* Ref: *Feibelman and Stumpf, Sandia National Laboratories*

NH3 Conference - Portland

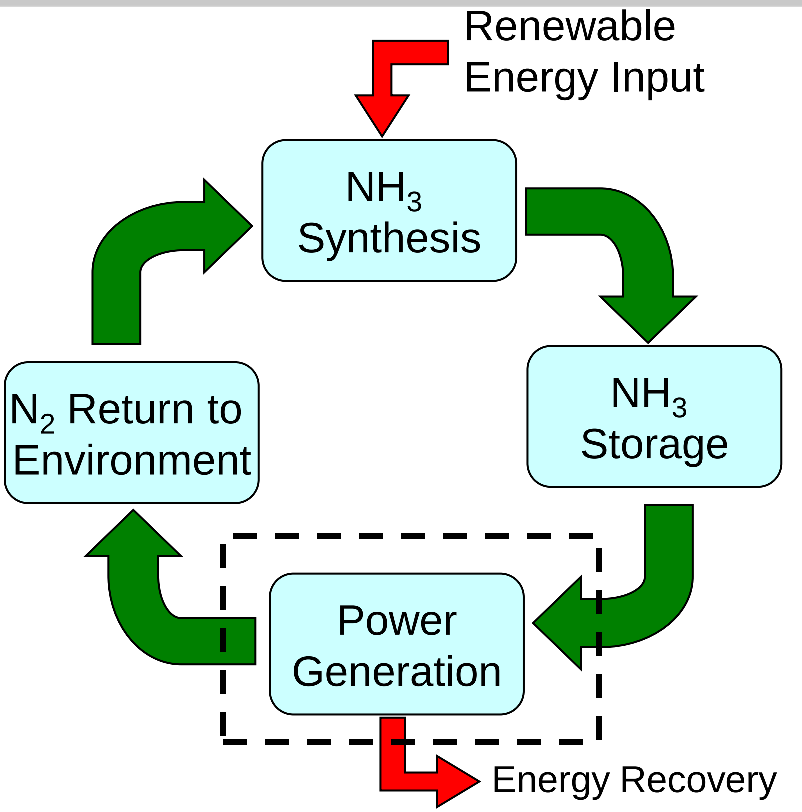
Gas Turbine Power Generation – Role of Ammonia

Transportation Advantages of Ammonia over Natural Gas

- Compression or refrigeration costs of ammonia shipping are far lower than natural gas.
- Liquid natural gas (LNG) is at -163 C, a deep cryogen. Ammonia at the ambient pressure is only at -33 C, a cold liquid.
- Compressed natural gas (CNG) is at 2,900-3,200 psi. Pressure of ammonia is ~200 psi.
- Flammability limits of natural gas is significantly wider.

Target Market 3 – Distributed Renewable Energy Generation

- Most of the renewable energy sources such a solar or wind have very low capacity factors (10-30%). This requires a backup power system.
- Instead of connecting to the grid (utilities companies would charge for this), use the excess power to make ammonia which can be stored and burned in a micro turbine to generate electricity and heat when needed.
- This requires the development of an efficient synthesis technology for ammonia (from water and air).
- Since ammonia is a widely used fertilizer, its use in electricity generation in rural/agricultural areas makes perfect economical sense.

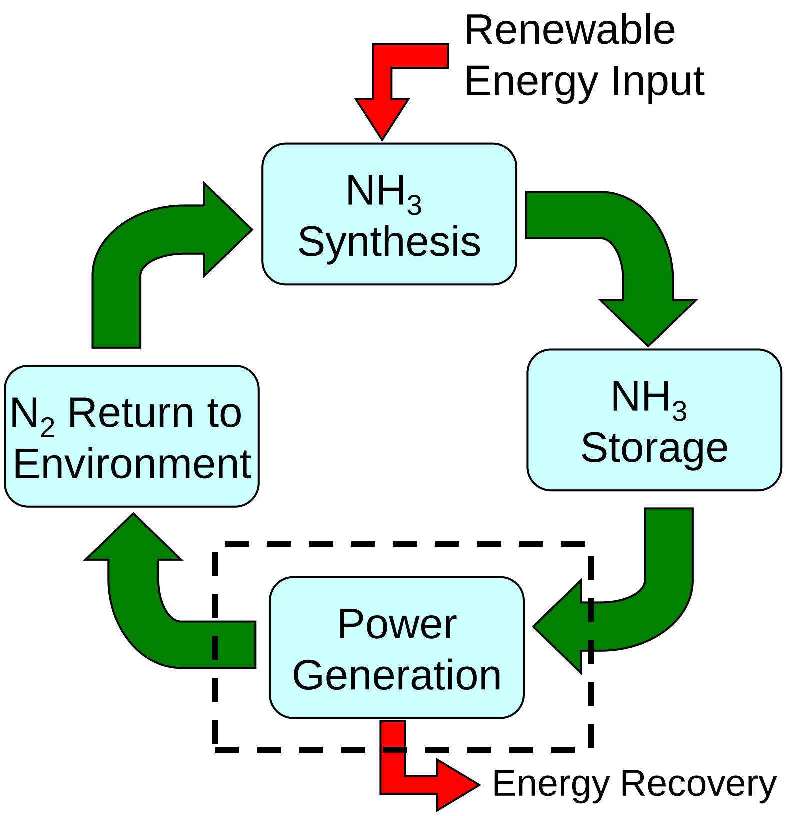


NH3 Conference - Portland

Gas Turbine Power Generation – Role of Ammonia

Target Market 4 – Enabling Technology for Stranded Renewable Energy Source

- Stranded Renewable Energy Sources: Most of the renewable energy sources such as solar, geothermal or wind are not accessible by the existing electric grid system.
- Extending the grid to remote areas is NOT economical. In most cases extension of the grid system is politically difficult (if not impossible).
- Ammonia as energy carrier has the potential to solve the Stranded Renewable Energy problem.
- Using a synthesis method such as SSAS ammonia can be produced at the stranded site from water and air.
- The produced ammonia can be shipped via trucks, railroad or pipelines to the power generation plants to generate electricity.



Ammonia Fired Turbines

NH3 Conference - Portland

Gas Turbine Power Generation – Fuels Comparison

Fuel	Fuel/air ratio*	Tcombuster* K at 20atm	Texhaust K at 1 atm	Enthalpy change (work) kJ/kg
Methane	0.058	2277	1260	1551
JP-4	0.068	2342	1313	1539
Ethanol	0.111	2295	1289	1546
NH3	0.164	2092	1114	1549

* Stoichiometric fuel/air combustion at a pressure ratio of 20:1

- NH3 requires higher fuel mass flow rate
- NH3 generates the same work output at lower temperature
- Or NH3 generates more power at the same temperature

NH3 Conference - Portland

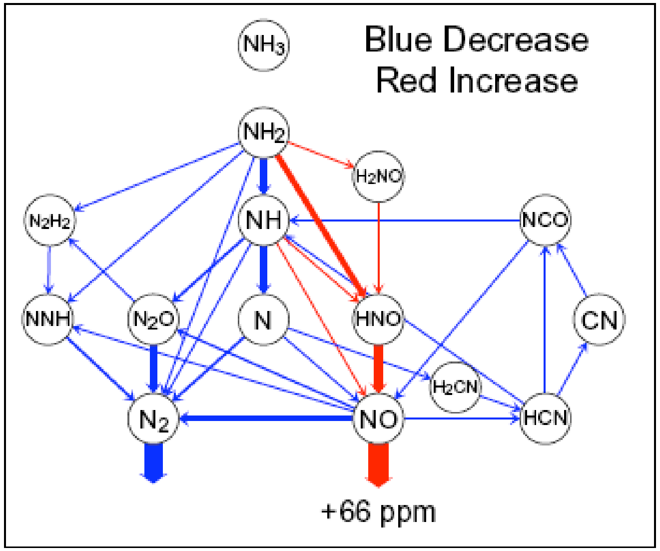
Past Experience with Ammonia Fueled Gas Turbines

History

- Ammonia as a turbojet engine fuel has been tested in 1960's
- At least two DoD programs (reports available)
- Some recent research activity in University of Florida
- No active programs as far as we know

Lessons Learned

- Ammonia is a satisfactory substitute for hydrocarbon fuels in a gas turbine engine
- Complexity and cost of engines using ammonia vapor combustors will NOT be significantly greater than existing hydrocarbon engines
- Use of ammonia would also lead to reduction of NOx emissions



Oxidization chemistry of ammonia is well established

Technical Challenges

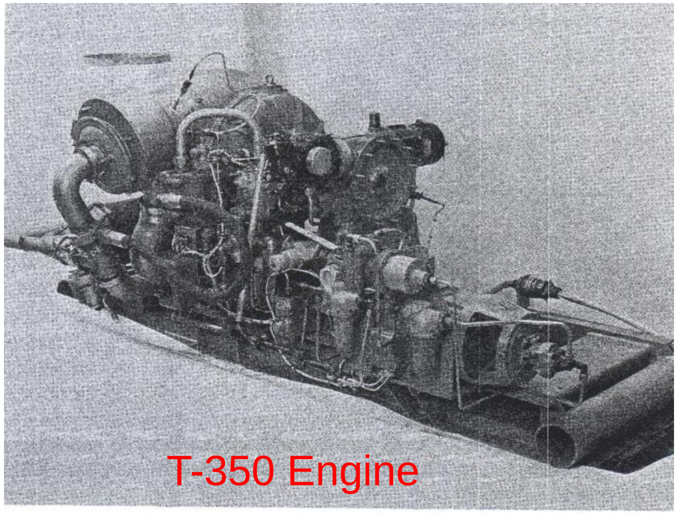
- Low flame temperatures and slow kinetics results in challenges with pure ammonia in a turbojet combustor
- Stable efficient combustion with liquid NH3 is problematic. Additives would help with this issue
- The DoD programs concluded that ammonia in the vapor phase can be burned in a turbojet combustor. This requires a heat exchanger to vaporize the ammonia
- Cracking helps flame stability

SPG Advancing Propulsion & Energy

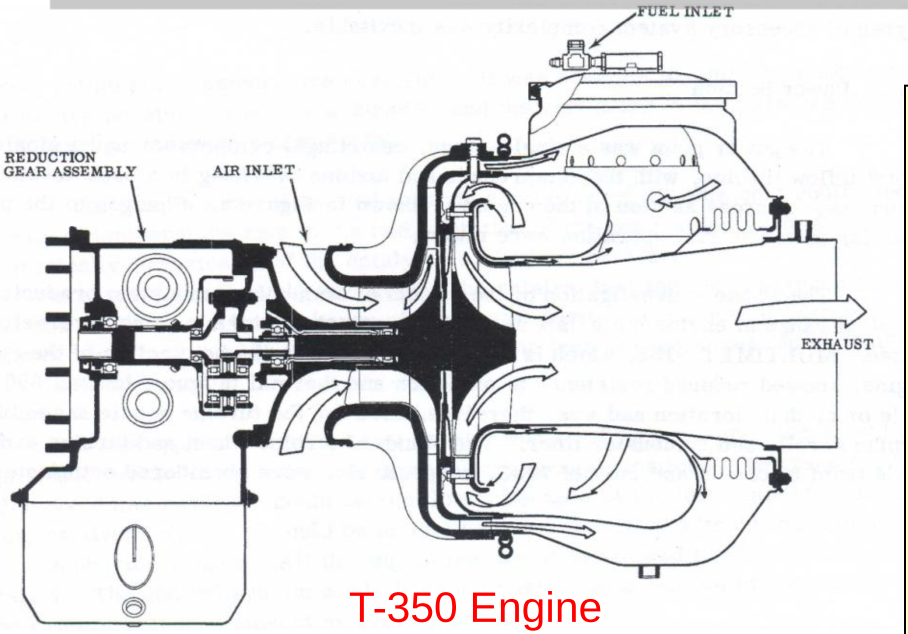
NH3 Conference - Portland

Past Experience with Ammonia Fueled Gas Turbines

- Investigations have been conducted by Solar Company and UC Berkeley in the 60's
- Solar used its 250 HP model T-350 single can burner engine.
- UC Berkeley studies were limited to subscale combustors
- Performance of the T-350 engine with ammonia is compared to the performance with JP-4
- Tests were limited to ammonia in vapor phase



T-350 Engine



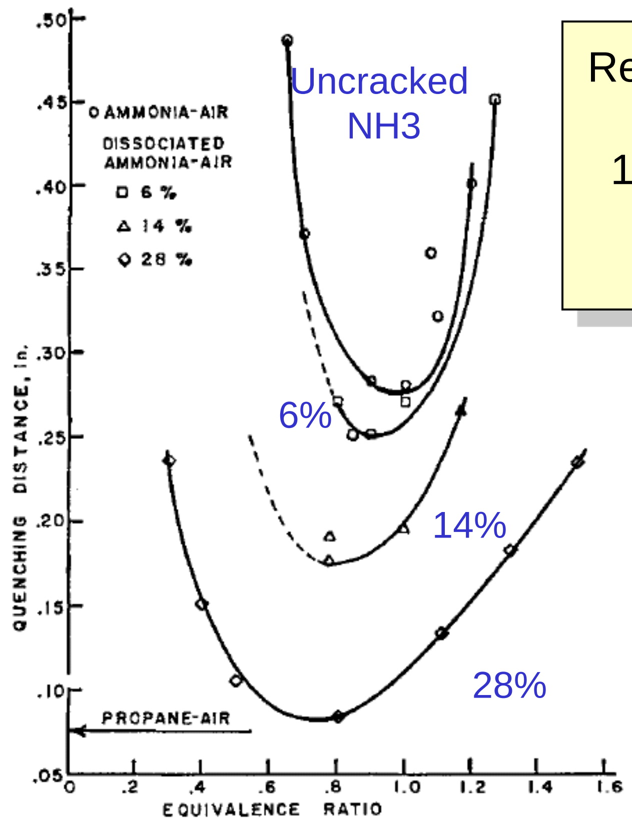
T-350 Engine

Some Observations

- Both vapor and catalyst combustors have been tested.
- Using ammonia at 2.35 times the HC fuels resulted in cooler turbine inlet temperatures at a given power.
- When the turbine inlet temperatures are matched, the ammonia engine resulted in a power increase of 10-20%.
- Efficiencies were high with the ammonia combustors.

NH3 Conference - Portland

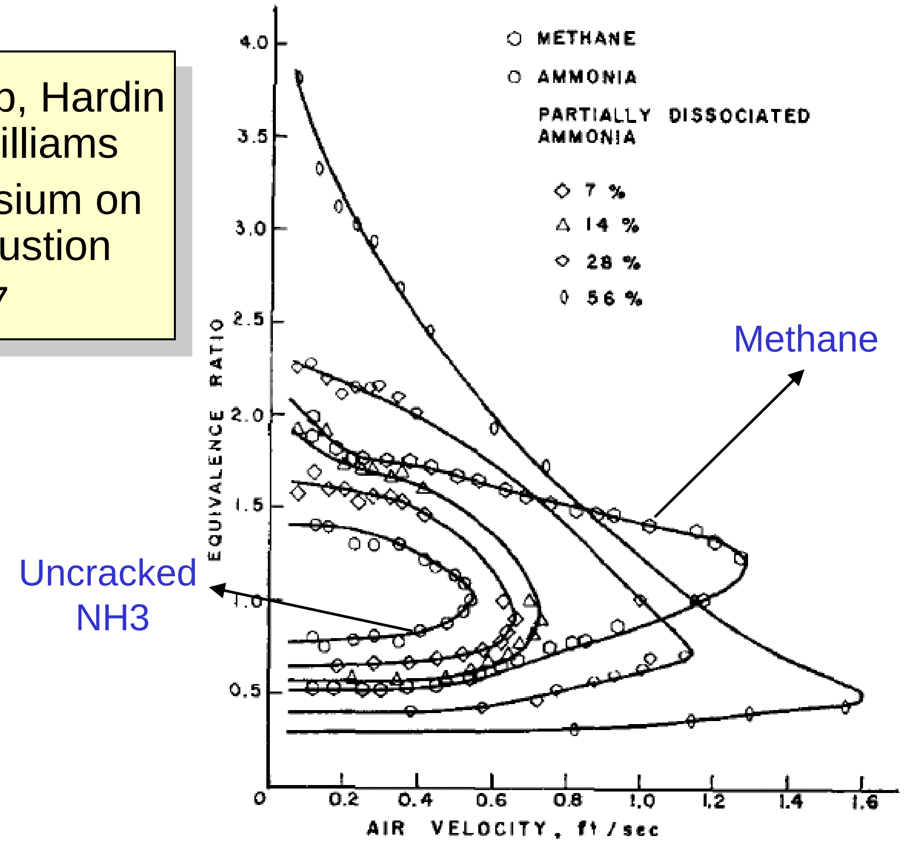
Ammonia/Air Combustion



Ref: Vercamp, Hardin and Williams

11th Symposium on Combustion

1967



- Uncracked NH3: Slow flame speed, large ignition energy, large quenching distance, poor flame stability
- Cracking is needed for 1) stability, 2) efficiency, 3) Low Nox emissions and 4) good power loading

Development Path

NH3 Conference - Portland

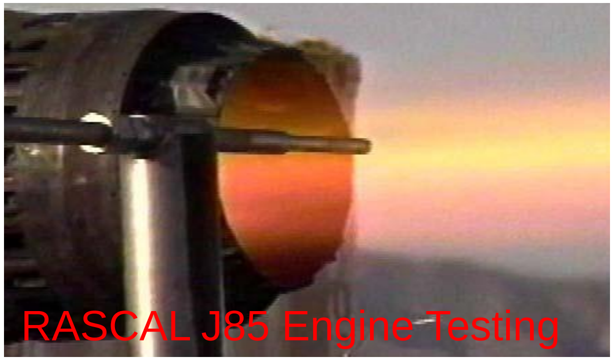
SPG's Core Competence

SPG personnel have broad experience in the areas

- Combustion, thermochemistry of fuels, design and analysis of gas turbines
- Testing of gas turbine engines and rocket motor systems

Hybrid Motor Testing

RASCAL Facility, Mojave CA



RASCAL J85 Engine Testing

SPG have access to several J79 and J85 engines and all test equipment from the RASCAL program

SPG's capabilities include

- Laboratory testing of fuel properties
- Testing of turbojet engines (AEROTEC test facility in Butte Montana)

SPG Advancing Propulsion & Energy

NH3 Conference - Portland

Development - Program Elements

Phase I – Feasibility (Funded by Montana Board of Research and Commercialization Technology)

- Objective: Evaluate the feasibility and economical/technical viability of the concept
- Conduct feasibility studies: Modeling of ammonia combustion, testing in combustors and design of fuel nozzle for J85 and J79 engines

Phase II – Technology Development

- Objective: Develop the necessary technologies to implement the concept
- Work includes: Fuel formulation and laboratory testing, engine cycle analysis, extensive engine testing (using engines such as J85 and J79 – two exist in the AEROTEC facility), development of fuel systems

Phase III – Pilot Plant

- Objective: Implement the concept on a small gas turbine power generation plant
- Work includes: Conversion of the existing facility to an ammonia fired gas turbine, evaluation of the economical viability of the concept
- Partner with an energy company

Phase IV – Implementation

- Objective: Convert existing gas turbine power generation facilities to burn ammonia and develop new ammonia-fired gas turbines if necessary
- Partner with a gas turbine producer

NH3 Conference - Portland

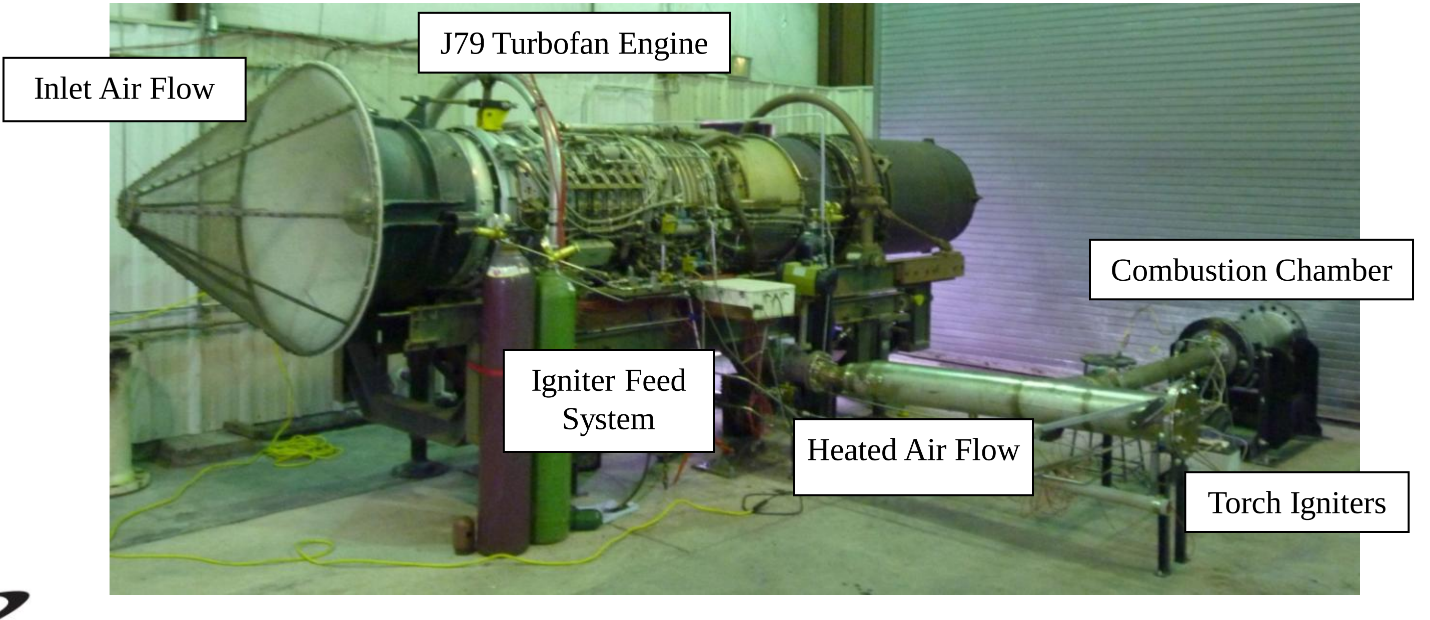
Phase I Progress

- Funded by State of Montana and SPG's IR&D
- Will be completed in 6-9 months
- Development of the air feed system has been completed
  - Facility evaluation tests have been conducted
- Development of the igniters have been completed
  - Igniter tests have been conducted
- Development of the control system has been completed
- Development of the DAQ system has been completed
- Design of the system has been completed
  - Combustor
  - Vaporizer
  - Mixer
- Fabrication of the test articles has been started
- Testing will start in late 2011

NH3 Conference - Portland

Test Rig Overview

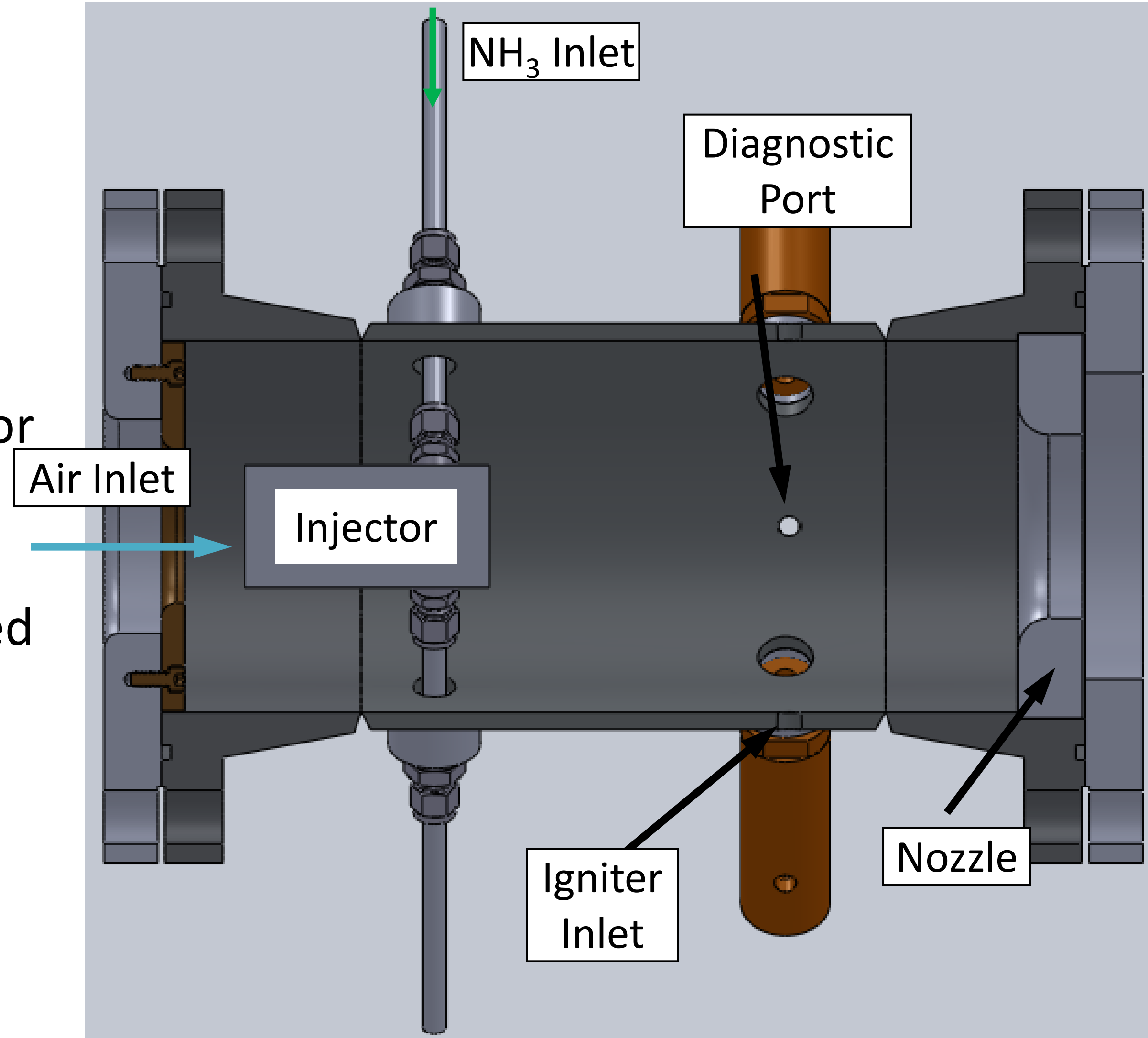
- Test rig designed to simulate J79 can combustor
- Bleed air from a J-79 turbofan engine supplies high pressure, hot air for combustion
  - Air flow rates of 8.0 kg/s can easily be achieved
- At full thrust, an NH3 mass flow rate of 0.690 kg/s required for stoichiometric mixture
- Supercharged NH3 will be used to avoid flow rate decay with time
- NH3 will be vaporized and mixed with N2/H2 to simulate cracking
- Extent of simulated cracking will be precisely controlled



NH3 Conference - Portland

Combustion Chamber

- Model one of the can combustors of J79
- Combustion Chamber:
  - Inner Diameter: 6”
  - Length: 14” length, inlet to nozzle face
- Try a number of injector configurations
- Dual CH_4/O_2 igniters
- Diagnostic ports located in aft-end of chamber
  - Pressures
  - Nox sensor
  - Temperature
  - Flow Rates



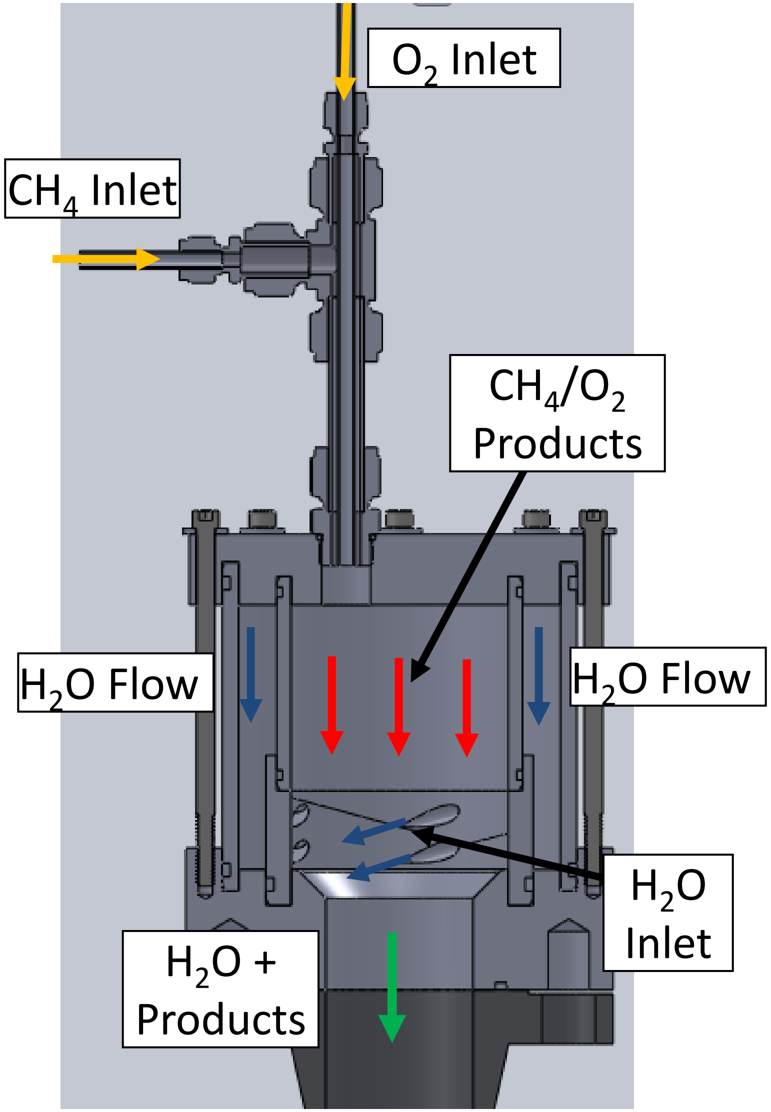
NH3 Vaporization Process

- Complete vaporization of NH_3 is desired for stable combustion.
- Vaporization at peak thrust level requires 841 kW, assuming NH_3 inlet temperature of 15°C.
- Accounting for heat exchange efficiency, power input > 900 kW could be required to fully vaporize.
- System designed to generate sufficient thermal energy for full vaporization.

NH3 Conference - Portland

Chemical Steam Generator

- Initially a chemical stem generator will be used to vaporize ammonia
- Hot exhaust gases of the gas turbine plant will be used in the next phase
- CH_4/O_2 reacted in water-cooled chamber
- Three injection locations to produce radially homogeneous mixture
- Water injected at aft of chamber, generating steam/product mixture
- Mass flow rates:
  - H_2O: 363 g/s
  - CH_4/O_2: 100 g/s
- Mixture has 900 kW available for vaporization



NH3 Conference - Portland

Heat Exchanger

- Outlet of steam generator is connected to heat exchanger
- High pressure, NH_3 compatible heat exchangers not readily available
- In house heat exchanger development is ongoing
- Shell and coil heat exchanger design to be implemented using stainless steel tubing
  - High pressure tubing allows NH_3 to be superheated without hazard of release into atmosphere
- Approximately 3.3 m^2 required to transfer required heat

Summary

- Ammonia is a very promising environmentally friendly energy storage/carrier
  - No CO_2 emission when oxidized
  - High hydrogen density
  - Easy to transport and store
  - Widely produced and used commodity
  - Triple use as fertilizer/industrial/fuel
- The major disadvantages that exist for its use in transportation systems does NOT apply to the power generation applications
- Existing oil or gas fired gas turbine plants can be easily converted to burn ammonia
- Some limited experience on using ammonia in gas turbines exist
- Potential to be more economical than the existing fossil based fuels
  - New production technologies are being developed to make ammonia from water and air
  - If ammonia is produced using the existing technology in areas where natural gas prices are low
  - Enabler for stranded renewable energy sources
- Additional application of ammonia in the power generation field would reduce the price (economics of scales) and would benefit its use as a fertilizer
- Successful use of ammonia in the power generation area would be beneficial for its use in the transportation systems

Thank You!

SPG
Advancing Propulsion & Energy

Safety Overview

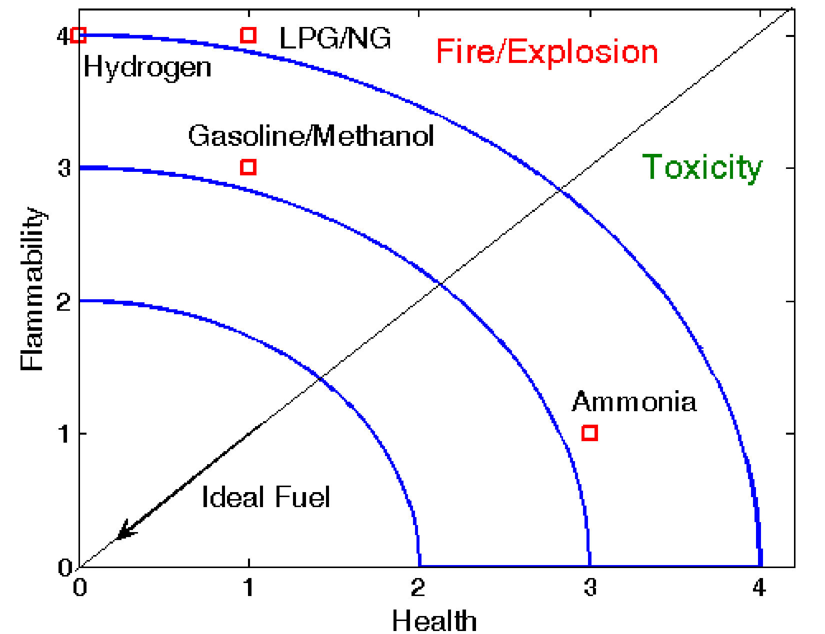
NH3 Conference - Portland

Safety – Overview

NFPA no. 704 classification is a good starting point to assess the safety of fuels

Substance	Health	Flammability	Reactivity
Ammonia	3	1	0
Hydrogen	0	4	0
Gasoline	1	3	0
LPG	1	4	0
Natural Gas	1	4	0
Methanol	1	3	0

0=No hazard, 4=Severe hazards



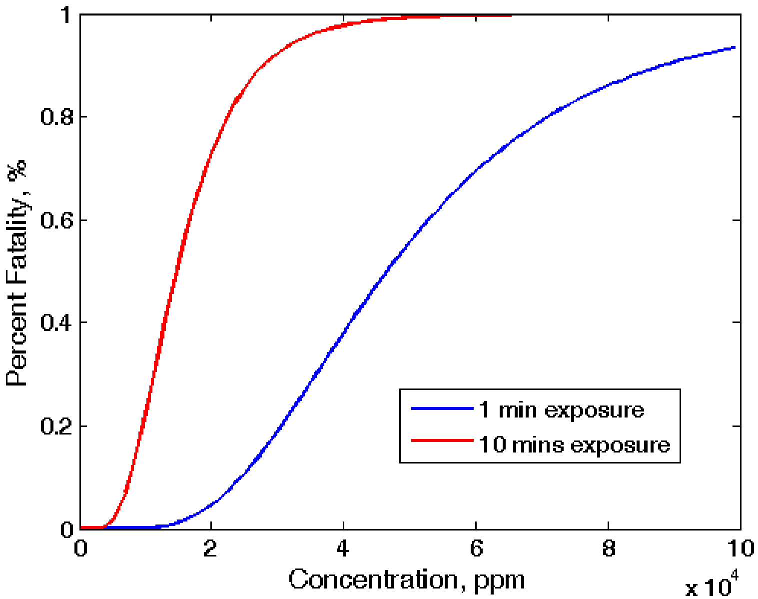
- There are serious hazards associated with all fuels
- With the exception of gasoline and methanol health related hazards of fuels other than ammonia are low
- Hazards associated with flammability are low in the case of ammonia
- Ammonia is rated as a toxic substance but NOT as a poison (NFPA Health: 3)
- With ammonia Fire/Explosion hazards of the other fuels are traded with the Toxicity hazard

NH3 Conference - Portland

Safety – Toxicity Hazard

- Ammonia is a toxic substance with the exposure limit of
  TWA: 25 ppm 8 hours
- LC50 level for 20 min. exposure is
  29,000 ppm

Effect	Ammonia Concentration in Air (by volume)
Readily detectable odor	20-50 ppm
No impairment of health for prolonged exposure	50-100 ppm
Severe irritation of eyes, ears, nose and throat, No lasting effect on short exposure	400-700 ppm
Dangerous, less than ½ hours of exposure may be fatal	2,000-3,000 ppm
Serious edema, strangulation, asphyxia, rapidly fatal	5,000-10,000 ppm



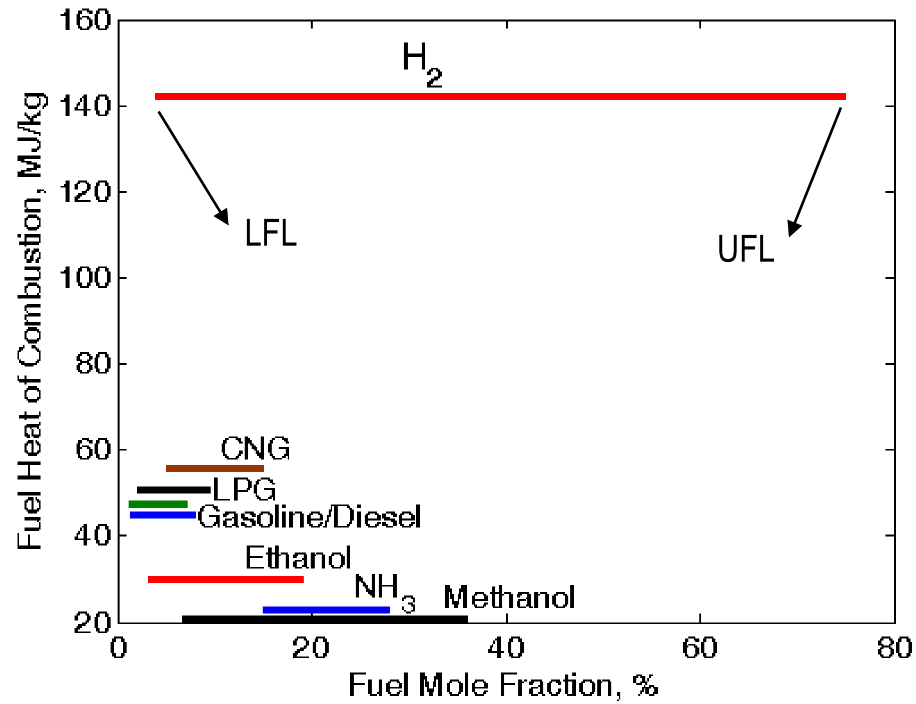
The following are the mitigating factors

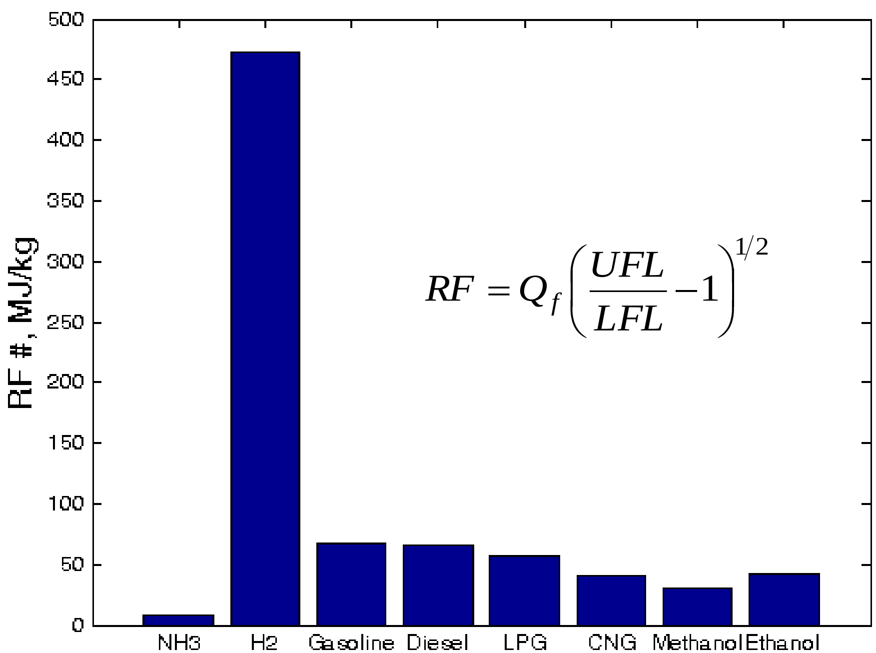
- Ammonia is lighter than air – plume moves up quickly, reducing the exposure times
- Perceptible odor at safe concentrations
- The "self-alarming" feature of ammonia is particularly useful since readily detectable odor concentration is well below the fatal level
- Ammonia is NOT a carcinogenic substance

SPG Advancing Propulsion & Energy

Safety – Fire/Explosion Hazard

- Ammonia has
  - Low heat of combustion
  - Narrow flammability limits
- Fire/explosion hazard for ammonia is very low





- RF index is used to assess the fire/explosion hazard of a flammable substance
- Higher RF # indicates more fire/explosion hazard
- RF number for ammonia is much smaller than the other fuels
- RF # of H2 is almost 100 times larger

NH3 Conference - Portland

Safety – Tank Rupture Hazard

PV Driven Explosions

- Energy associated with high pressure gases
- H2 and CNG are stored at extremely high pressures resulting in substantial PV energies in the storage vessel

BLEVE's

- Explosive boiling of a saturated liquid
- Both ammonia and LPG are subject to BLEVE events
- Fatal BLEVE events have been reported with both substances

Fuel	TNT equivalent for 1 kg of fuel	Relative Mass Basis	TNT equivalent for 1 MJ of fuel	Relative Energy Basis
Hydrogen @ 10,000 psi	570 g	50	4.1 g	7
Ammonia @ 298 K	11 g	1	0.6 g	1

- No combustion energy is used in the calculations
- Reported ammonia BLEVE's are limited to large industrial systems
- BLEVE's are unlikely in the small tanks of transportation systems
- Melting liners can be used to prevent fire induced BLEVE's

Blast wave and fragment hazards associated with the rupture of a small ammonia tank is negligible
The rupture of GH2 and CNG vessels present a significant risk

SPG Advancing Propulsion & Energy

NH3 Conference - Portland

Safety – Ammonia Vehicle Safety Studies

Two comprehensive studies on the safety of ammonia as a transportation fuel exist

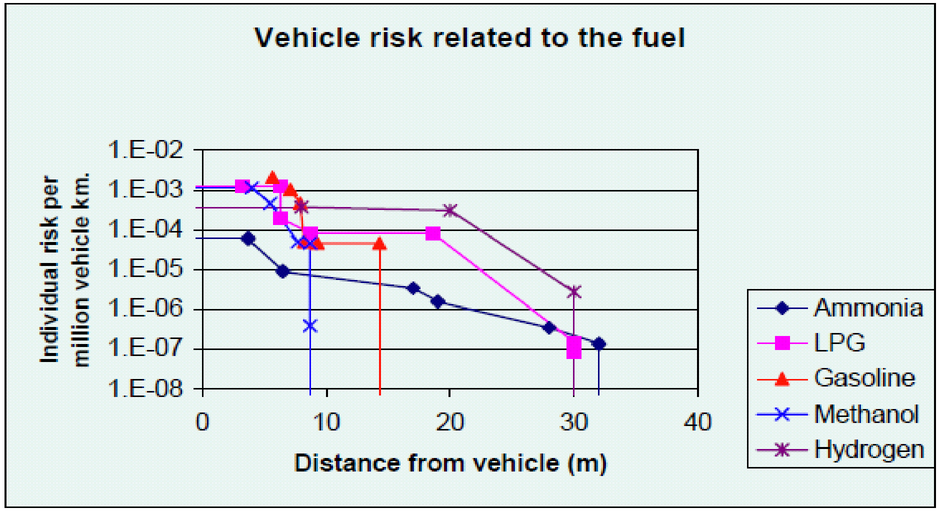


Figure 10 Comparison of individual risk as function of distance to a vehicle

Risk (per million km) is plotted against the distance from the vehicle for various fuels. Flash fire, heat radiation, explosion and toxicity damage modes are included in the calculations

Ref.: "Safety Assessment of Ammonia as a Transport Fuel", RISO National Laboratory, Denmark, 2005

The other study, by Quest Consultants of Norman, OK, came to a similar conclusion: the safety issue is NOT a show stopper for ammonia as a transportation fuel

NH3 Conference - Portland

Safety – Experience Base & Safety Record

- Ammonia is a widely used commodity
- Extensive knowledge base exists in
  - Production of ammonia
  - Transportation of ammonia
  - Storage of ammonia
  - Design of ammonia systems (including a comprehensive list of compatible materials)
  - Safe handling
  - Emergency procedures

- Ammonia is regularly handled by farmers in relatively large quantities
- Ammonia related accidents are rare in agriculture
- By following a set of relatively simple rules, ammonia can be handled safely by people with minimal training

Excellent data base exists on ammonia related accidents

Ammonia has an excellent safety record

NH3 is overall as safe or safer than any other fuel

SPG Advancing Propulsion & Energy