A Comparison of Combustion Promoters for Ammonia

and

Two Ways to Run Engines on Ammonia as the Only Fuel

GSG

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Summary of Ammonia Engine Progress

- Hydrocarbons, Hydrogen & Oxygen as Combustion Promoters for Ammonia
- Summary of Operating Maps
- Ammonia/Oxygen Test Engine Results
- Ammonia Flame Cracker
- Conclusion

Combustion of $0.79N_2 + 0.21O_2 + 0.28NH_3$

- Works only for special cases, for example WOT, 12:1, 1000 RPM, warmed up when ammonia is burned with air.
- Cold Start? Not reliable on ammonia/air mixture.
- Can't idle on ammonia/air mixture.
- Can use gasoline promote ammonia combustion and this is dual fuel.
- But for ammonia as the only fuel, and air as the only oxidizer:
  - **Combustion Promoter from air = Oxygen!**
  - **Combustion Promoter from ammonia = Hydrogen!**
    - **Ammonia/Hydrogen Rough Limit.**
    - **Or: Crack all ammonia to H_2 and burn the H_2 with air!**

Gasoline/Air, H_2/Air, and O_2/NH_3 Mixtures are Combustion Promoters for Additional NH_3/Air.

- $(0.79\ N_2 + 0.21\ O_2) + 0.024b\ C_6H_{11} + 0.28(1\text{-}b)\ NH_3 \Rightarrow$
$(0.93 - 0.14b)\ N_2 + (0.42 - 0.288b)\ H_2O + 0.144b\ CO_2$

Combustion Promoter is Gasoline/Air

- $(0.79\ N_2 + 0.21\ O_2) + 0.42b\ H_2 + 0.28(1\text{-}b)\ NH_3 \Rightarrow$
$(0.93 - 0.14b)\ N_2 + 0.42\ H_2O$

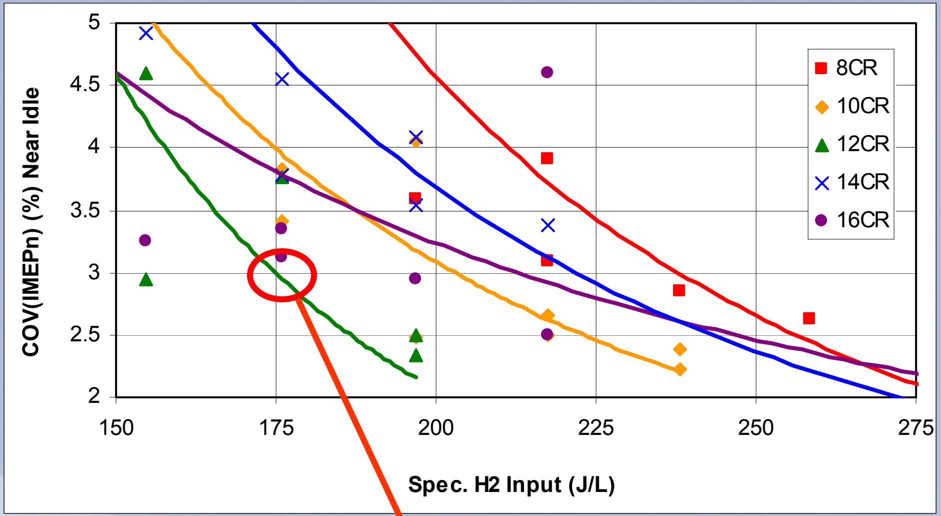
Combustion Promoter is Hydrogen/Air

- $(1\text{-}b)(0.79\ N_2 + 0.21\ O_2) + 0.21b\ O_2 + 0.28\ NH_3 \Rightarrow$
$(0.93 - 0.79b)\ N_2 + 0.42\ H_2O$

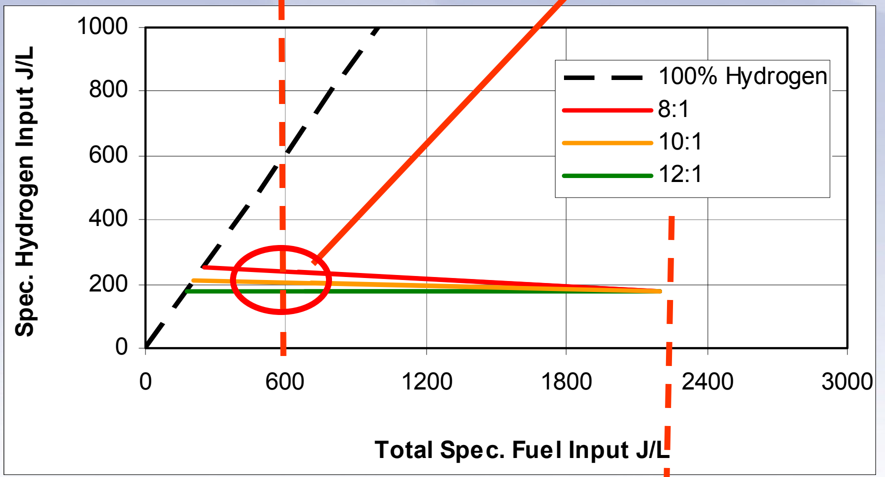
Combustion Promoter is Oxygen/Ammonia

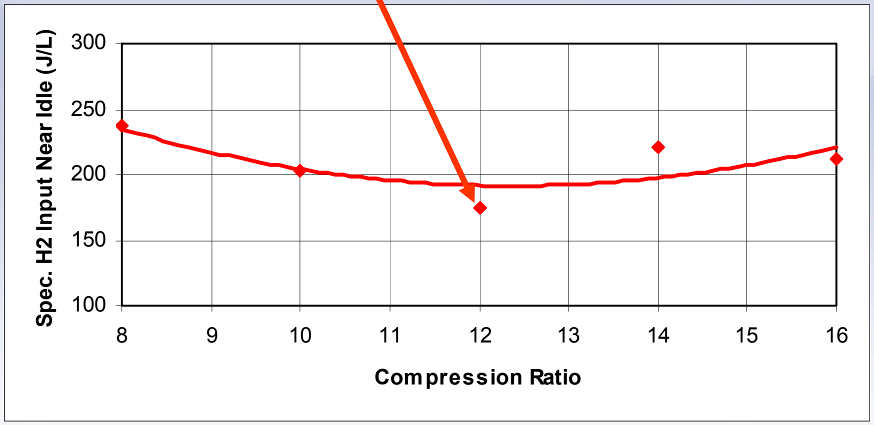
Rough Limit at 1600 RPM for Hydrogen

Rough Limit is determined by Combustion Promoter input at COV(IMEP) = 3% at light load Hydrogen can be obtained by cracking Ammonia!



Idle

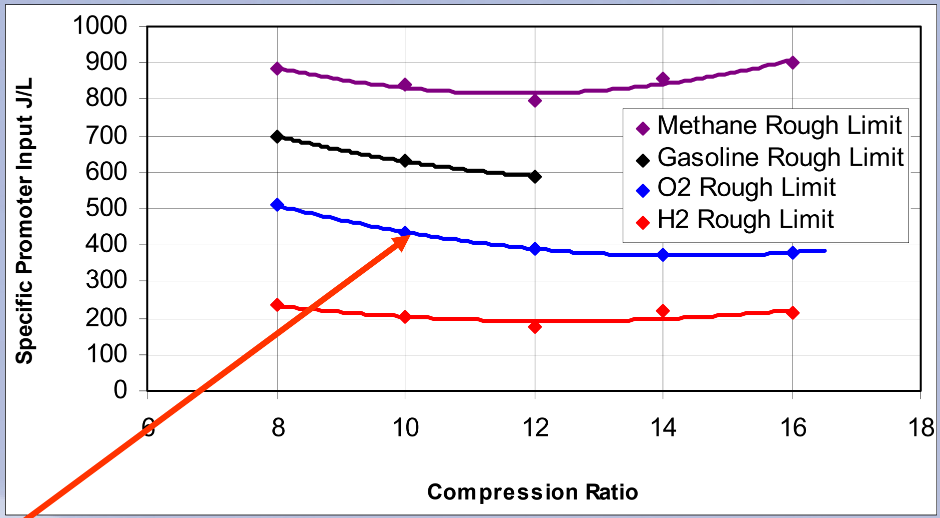




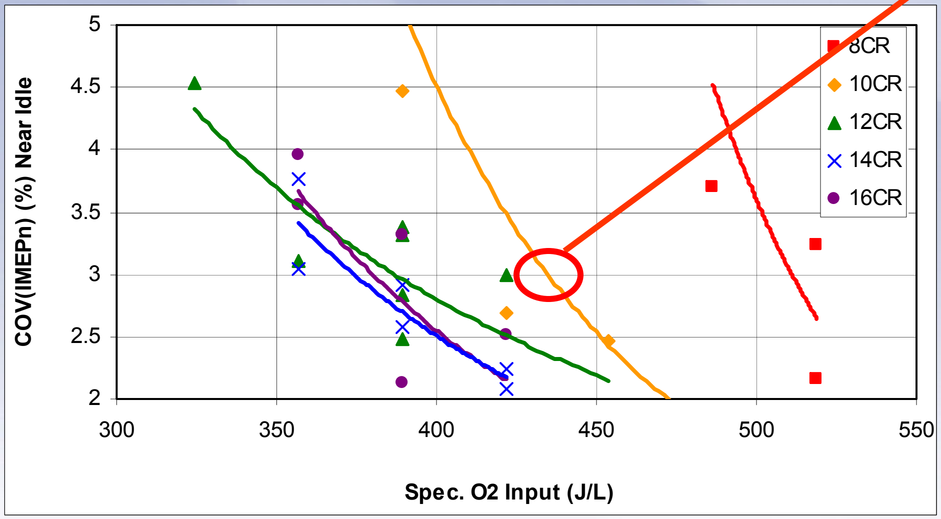
WOT

O_2 Rough Limit at 1600 RPM and ~ Idle

Oxygen is a Combustion Promoter Obtained from Air!



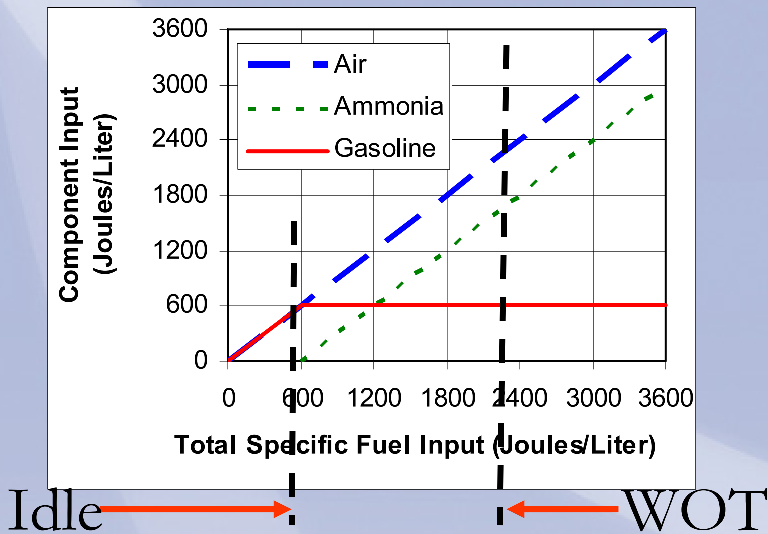
Oxygen curve is generated by COV(IMEP) crossings at 3%

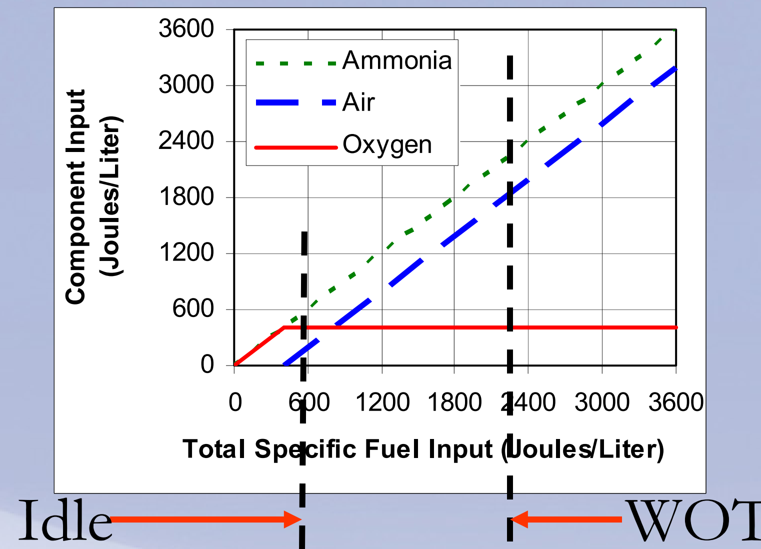


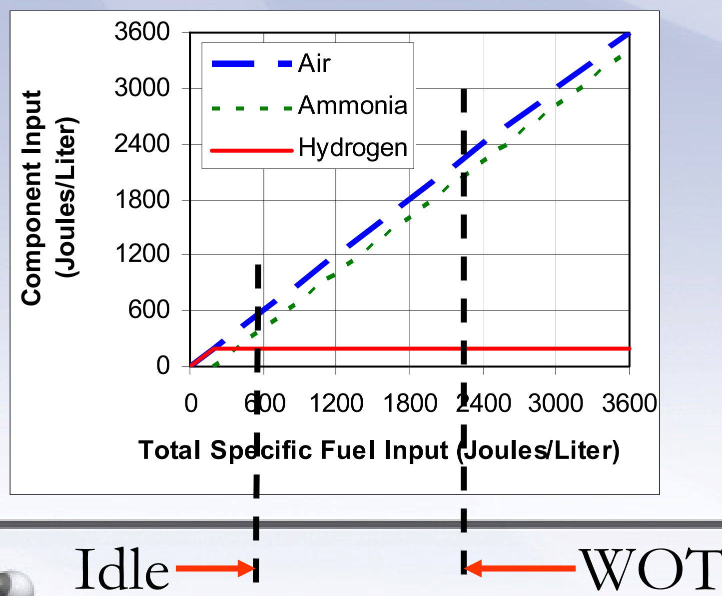
Rough Limit Comb. Promoter Input at 12:1, 1600 RPM:

- Hydrogen/Air ~200 J/L
- Oxygen/Ammonia ~400 J/L
- Gasoline/Air, ~600 J/L
- Methane/Air ~800J/L

Operating Maps for 1600 RPM, 12:1 Rough Limit







At Stoichiometric, the Chemical Equivalence Relationships are:

- Air = Gasoline + Ammonia
- Air = Hydrogen + Ammonia
- Ammonia = Air + Oxygen

Small Test Engine for NH_3/O_2

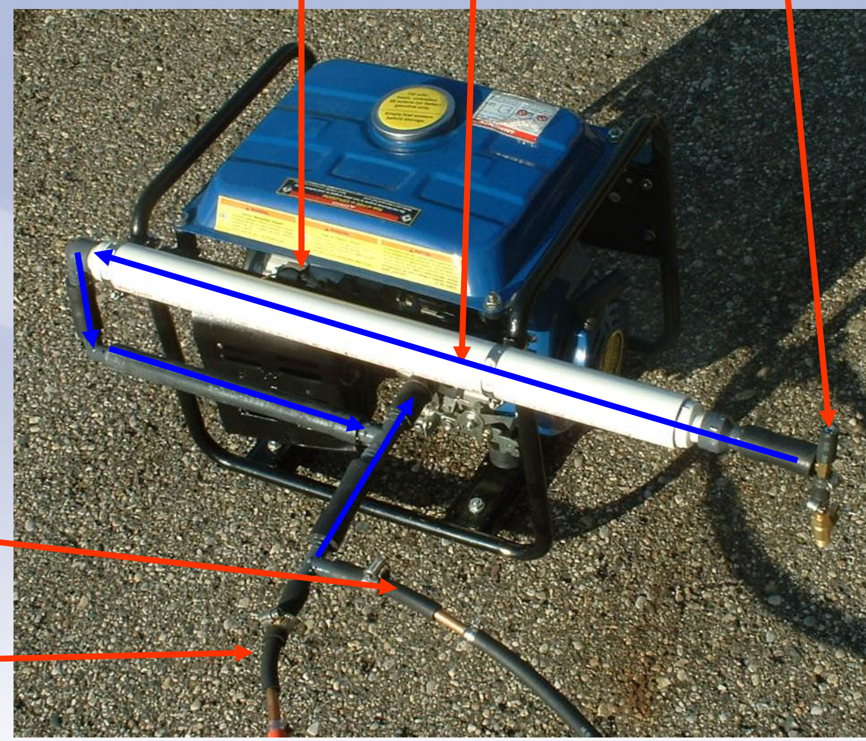
- Constant Oxygen Fraction for air+O_2 portions:
- $(1 - X)N_2 + (X)O_2 + (4X/3)NH_3 \Rightarrow$
  $(1 - X/3)N_2 + (2X)H_2O$
- X = 0.21 (21%) for Air

- Compression Ratio ~ 6:1
- 3600 RPM
- Fixed Spark Timing ~ 20 deg BTC
- COLD-START CAPABLE!
  (Easier than gasoline!)
- Operates without Ammonia Cracker.

Oxygen Sensor

Intake Plenum

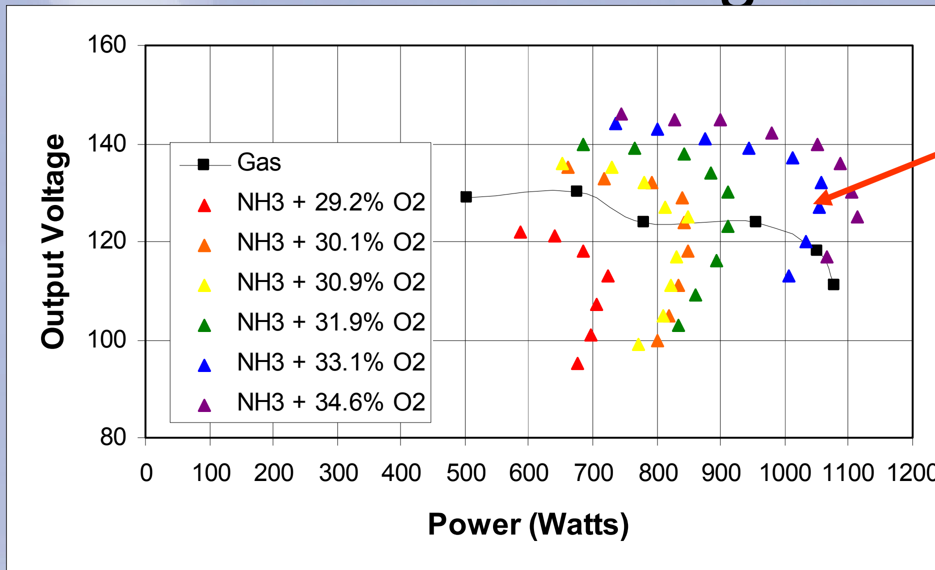
Air Pinhole with Fine Adjustment for Stoich.



Oxygen Inlet with Pinhole

Ammonia Inlet with Pinhole

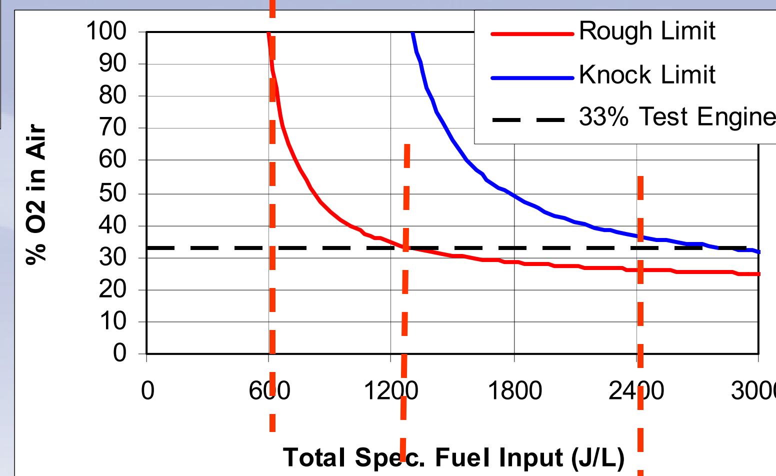
Small Test Engine Results for NH_3/O_2

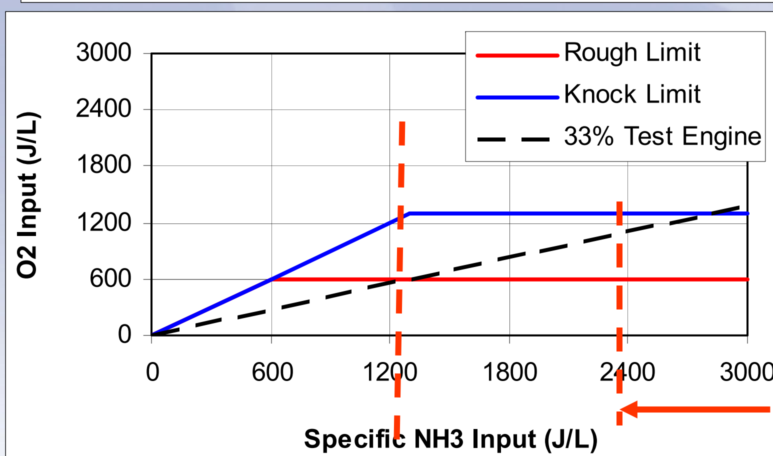


When the Oxygen Fraction of the Air/O_2 portions is 33%, Engine has Same WOT Power as for Gasoline!

Spark Adv. ~ 20 degrees → Not MBT?

Idle





WOT

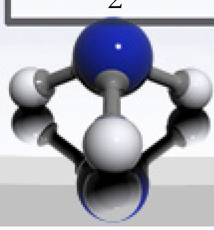
WOT

O_2 < Rough Limit -> Runs Rough

O_2 > Rough Limit ->Wastes O_2

O_2 < Rough Lim.

O_2 > Rough Lim.



Same Engine now with Ammonia Flame Cracker

Ammonia Cracker Output

- $0.79N_2 + 0.21O_2 + 0.42H_2 + 0.4\text{-}0.6(\text{Inert Gases}) \Rightarrow$ Nitrogen and Water from Engine Combustion

- Operates without Oxygen Separator.
- Additional Inert Intake Gases Buffer Against Knock and Backfire, and limit NOx emissions.

- COLD-START CAPABLE!
- VERY LITTLE OR NO NH3 ENTERS THE ENGINE!

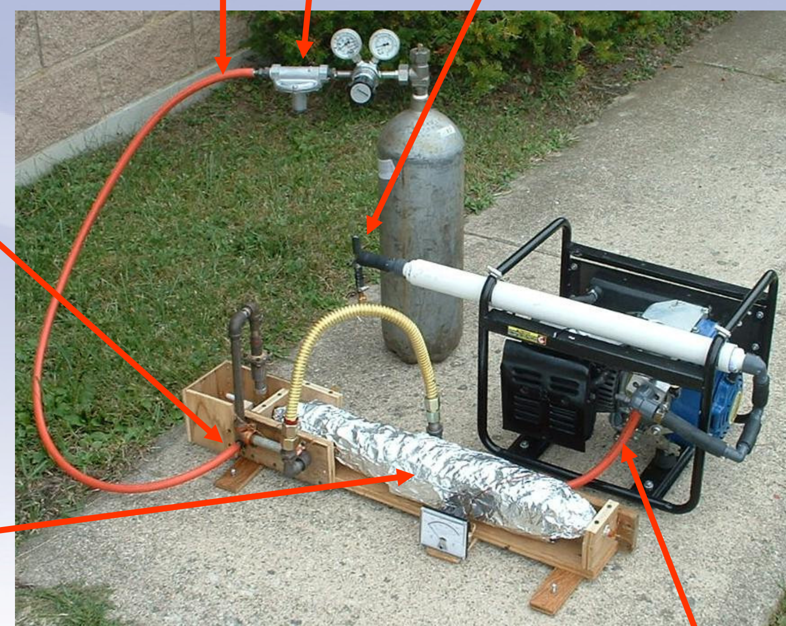
"Zero" Regulator

NH_3 Line

Air Pinhole with Fine Adjustment for Stoich.

Air/NH_3 pinhole mixer for Cracker

Ammonia Cracker



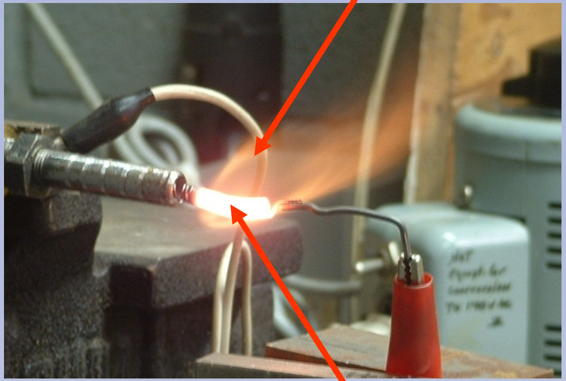
H_2 Line into Engine

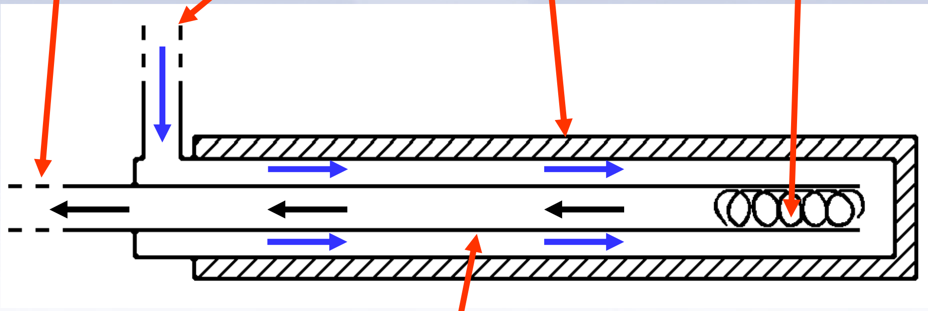
How the Ammonia Flame Cracker works

- Ideal Cracker Combustion::

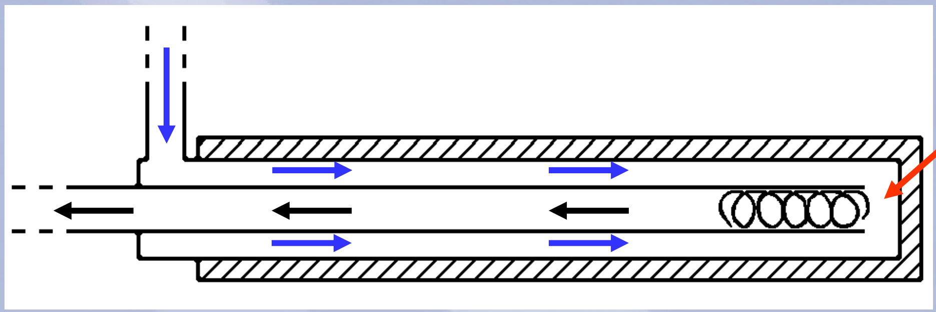
$$0.79N_2 + 0.21O_2 + 0.28\varphi NH_3 \Rightarrow$$
$$0.42H_2O + (0.79 + 0.14\varphi)N_2 + 0.42(\varphi - 1)H_2$$

- Gas is heat exchanged to expend less energy bringing NH_3 up to cracking temperature and to cool H_2 product.
- Heat released by combustion is absorbed by cracking.
- Filament resistively heated to start, then turned OFF during normal operation.
- Very high effective flame speeds ≥ 30-40 meters/sec.



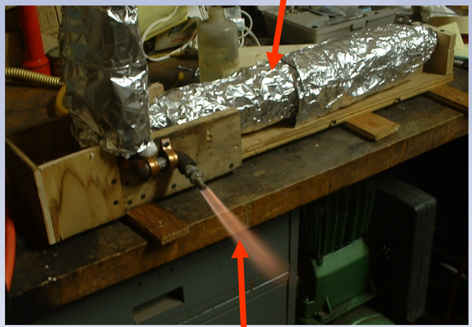


Ammonia Flame Cracker Analysis

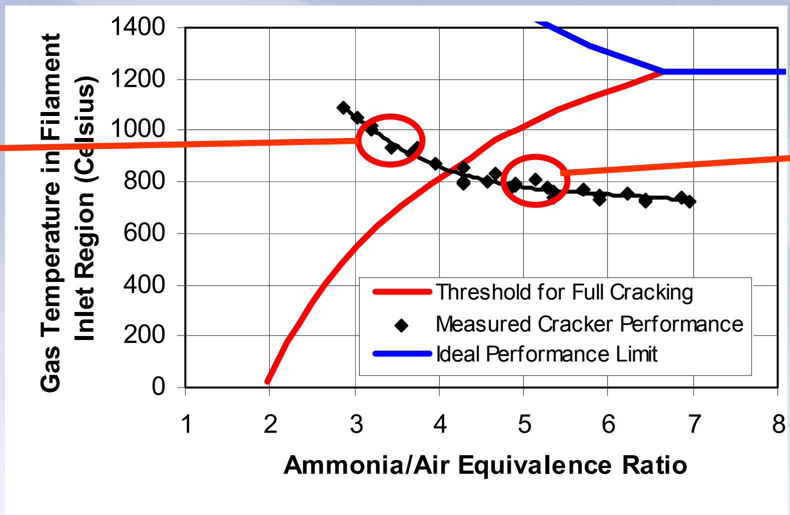


Gas Temperature in Filament Inlet Region is Initial Temperature before Reactions Start

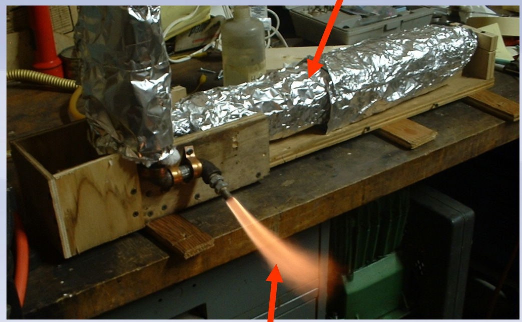
Ammonia Cracker



Very Little NH_3
Mostly H_2

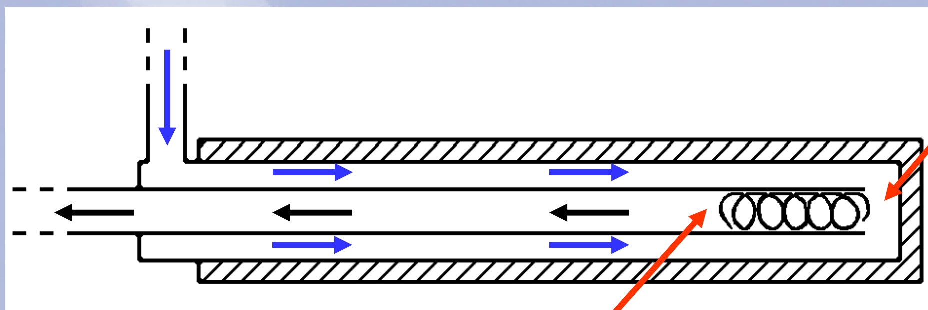


Ammonia Cracker



High NH_3 Content

Ammonia Flame Cracker Theoretical Operating Limit

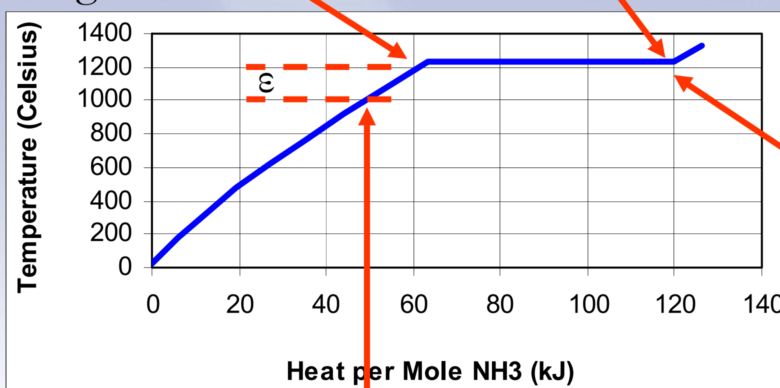


Gas Temperature in Filament Inlet Region is Initial Temperature before Reactions Start

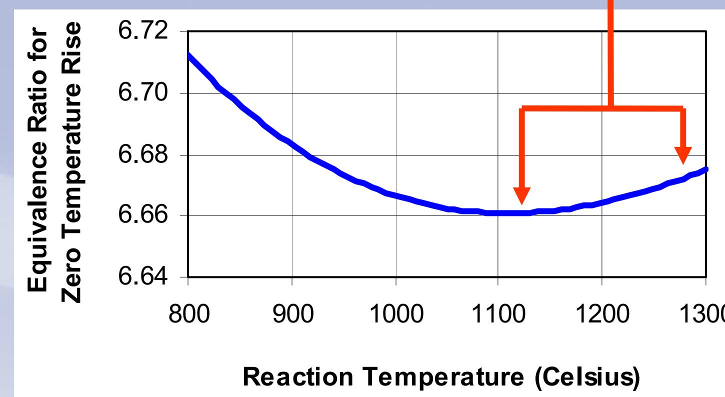
Cracking Range. Varies with Throughput Rate.

Post-Reaction Temperature

NH_3 Cracking begins.



NH_3 Fully Cracked



- If $\varepsilon \rightarrow 0$, then Reactions are balanced for Zero Temperature Rise.
- Worst Case Theoretical Maximum Full-Cracking Equiv. Ratio = 6.66

Gas Temperature in Filament Inlet Region might be 1000 C, For Example.

Conclusions

- CH_4 (800J/L), Gasoline (600J/L), O_2 (400J/L), and H_2 (200J/L) are useful Combustion Promoters for NH_3.
- Engines can work on 100% Ammonia without cracker when Oxygen is used, and Cold-Start is as Easy as for Gasoline.
- Ammonia Flame Cracking can be used to run on NH_3/H_2 Rough Limit OR 100% Hydrogen. Easy Cold-Start, and the Cracker can be run so that the Engine sees only trace quantities of Ammonia, or none at all.
- Theoretical Performance Limit of Ammonia Flame Cracker with Zero Losses: Full Cracking at Equivalence Ratio = 6.66, Product containing ~52% H_2 by volume, and NH_3-to-H_2 Thermal Conversion Efficiency = 97.3%, on an LHV energy basis.