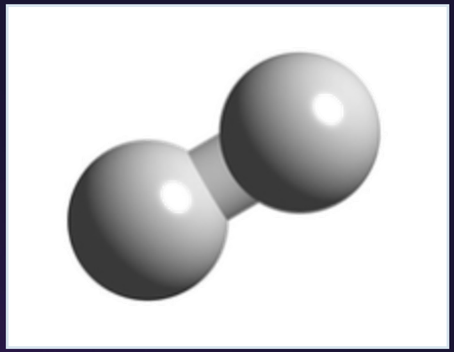
Ammonia and other e-fuels as a gas turbine fuel

Karl-Johan Nogenmyr
Siemens Energy AB
Finspång

Siemens Energy is a registered trademark licensed by Siemens AG.

Restricted © Siemens Energy, 2022

E-fuels… but H2 is always there!

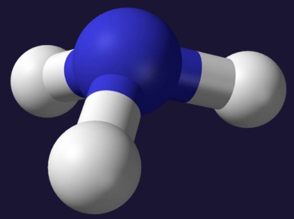


- E-fuels means a liquid fuel made of inert substances and electricity.

- Typically the syntesis starts with hydrogen from electrolysis, i.e. green hydrogen (as it only makes sense to make it from emission free energy)

Methods exist to produce similar liquid fuels from fossil fuels – but that's called "gas to liquid" (GTL) fuels, or when from biomass BTL.

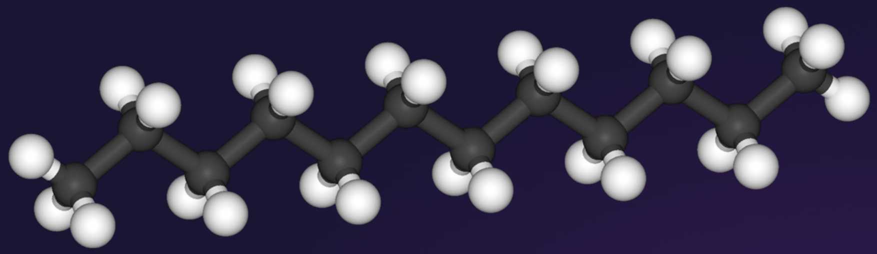
Different relevant e-fuels



Ammonia, 18.6 MJ/kg

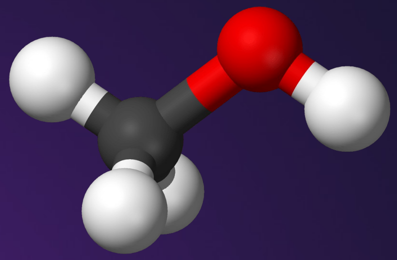
Electricity to LHV ~50%
Liquid at
-33°C @ 1 atm
8 bar(a) @ 20°C
Industrialized production
Highly toxic

Drawback:
Immature combustion technology



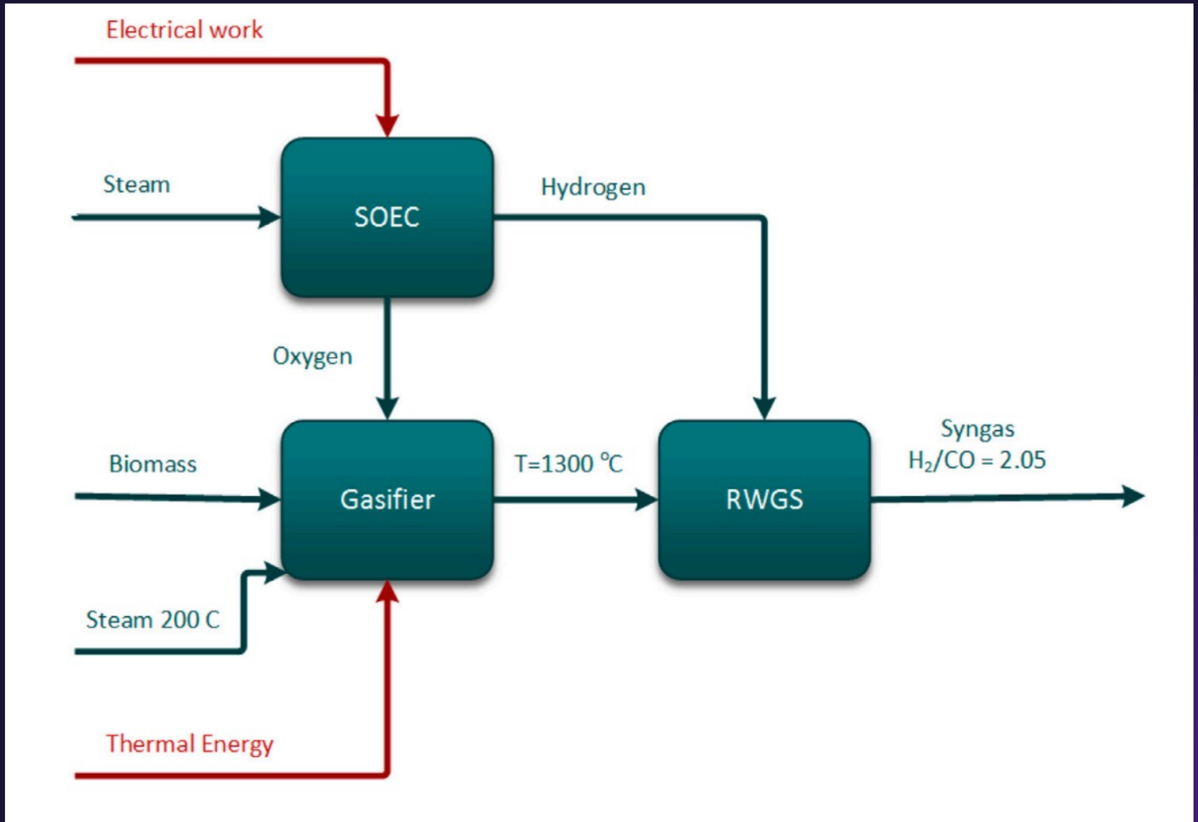
FT diesel, 44 MJ/kg
“Classic Diesel fuel”
Low level of pollutants
Non-toxic
When produced as a “e-bio-fuel”
50-60 % energy to LHV (Gebart)
40% electricity to LHV when produced from CO_2 and H_2

Drawback:
Suitable to produce from biomass – limited resource
Direct Air Capture not on industrial scale yet



Methanol, 22.7 MJ/kg
Electricity to LHV ~50%
Liquid at STP
Less toxic than NH_3
More of a conventional fuel
Gaseous injection saves 3% fuel!
Drawback:
Need a CO_2 source
Direct Air Capture not on industrial scale yet

Fischer-Tropsch Diesel fuel from biomass



- Use O2 from an electrolyzer to gasify biomass
- Add H2 from electrolyzer to syngas

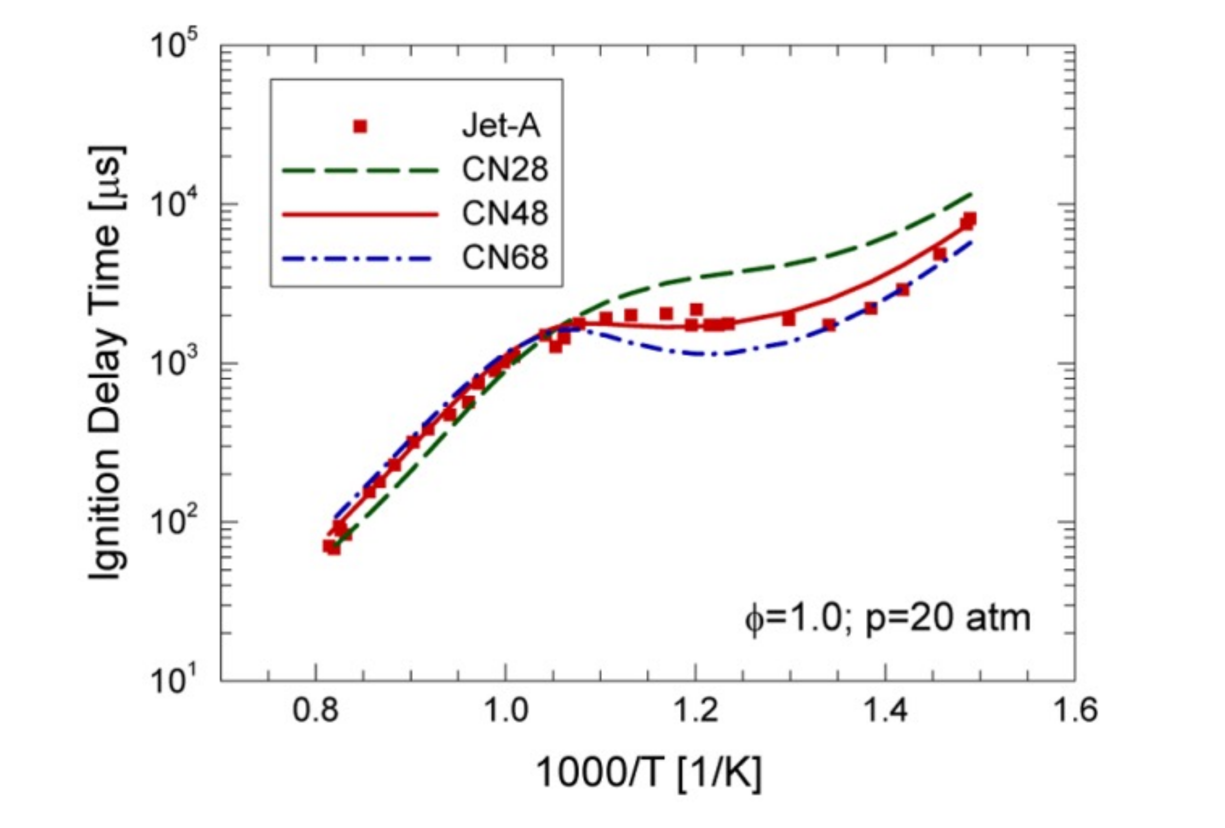
- Get suitable C/H ratio in off-gas

- 50-60 % energy (bio + electricity) to LHV

- Almost 100% "carbon efficiency"
  i.e. use all the collected C-atoms

Putta, K. R., Pandey, U., Gavrilovic, L., Rout, K. R., Rytter, E., Blekkan, E. A., & Hillestad, M. (2022). Optimal Renewable Energy Distribution Between Gasifier and Electrolyzer for Syngas Generation in a Power and Biomass-to-Liquid Fuel Process.

FT Diesel (and similar) as gas turbine fuel



- Commercially available fuels may be tailored for Diesel piston engines
- High Cetane number wanted – fast auto-ignition (HVO100 > 70)
- This is not what we want in typical lean premixed systems

Fan, Weiwei & Jia, Ming & Yachao, Chang & Xie, Mao-zhao. (2015). Understanding the Relationship between Cetane Number and the Ignition Delay in Shock Tubes for Different Fuels Based on a Skeletal Primary Reference Fuel (n -Hexadecane/Iso-cetane) Mechanism. Energy & Fuels. 29. 150416074949000. 10.1021/ef5028185.

Green fuel capabilities and roadmap

Medium gas turbines with DLE

SIEMENS energy

	Current	Near term	Road map
Gas phase	**H_2 40 – 75%** **Biogas** **50% cracked ammonia[1]** SGT-800/700/600	**H_2 100%** (latest 2025) SGT-800/700/600 **100% cracked ammonia[1]** SGT-800/700/600	**H_2 100%** SGT-750 **Ammonia**
Liquid phase	**Biodiesel** HVO100[2]		**Methanol** **FAME[3] (i.e., RME)**

1: Fully cracked (hydrogen/nitrogen mix) SGT-800/700/600
2: HVO = Hydrogenated Vegetable Oil
3: FAME= Fatty Acid Methyl Ester

Siemens Energy is a registered trademark licensed by Siemens AG.
Unrestricted © Siemens Energy, 2020

What about ammonia

- There are significant challenges in using it as a gas turbine fuel
  - Low flame speed
  - Massive amount of NOx
  - Significant amount of N2O could be formed – GWP of ~300
  - Toxic
- Cracking, partly or completely, back to H2+N2 can remedy these drawbacks
- From a system perspective, it makes sense to pressurize ammonia in liquid form, evaporate and crack using exhaust heat
  - **But: how well does potential catalysts work at these conditions?!**

Rich NH_3 flame surrounded by H_2 flame
Samuel Wiseman, NTNU

Formation of nitrogen and oxygen oxides

In "classical" hydro carbon (and hydrogen) combustion

- NO and NO2 formation is driven by "long residence time in hot zones"
- Pollutants formation rate grows exponentially beyond ~1500 °C (so the fuels flame temp is important – challenge for hydrogen)
- … if there is an availability of O-atoms (radicals)

That's why lean premixed has been the preferred choice to mitigate NOx - we can keep the maximum temperature down

When fuel contains (a lot) of nitrogen

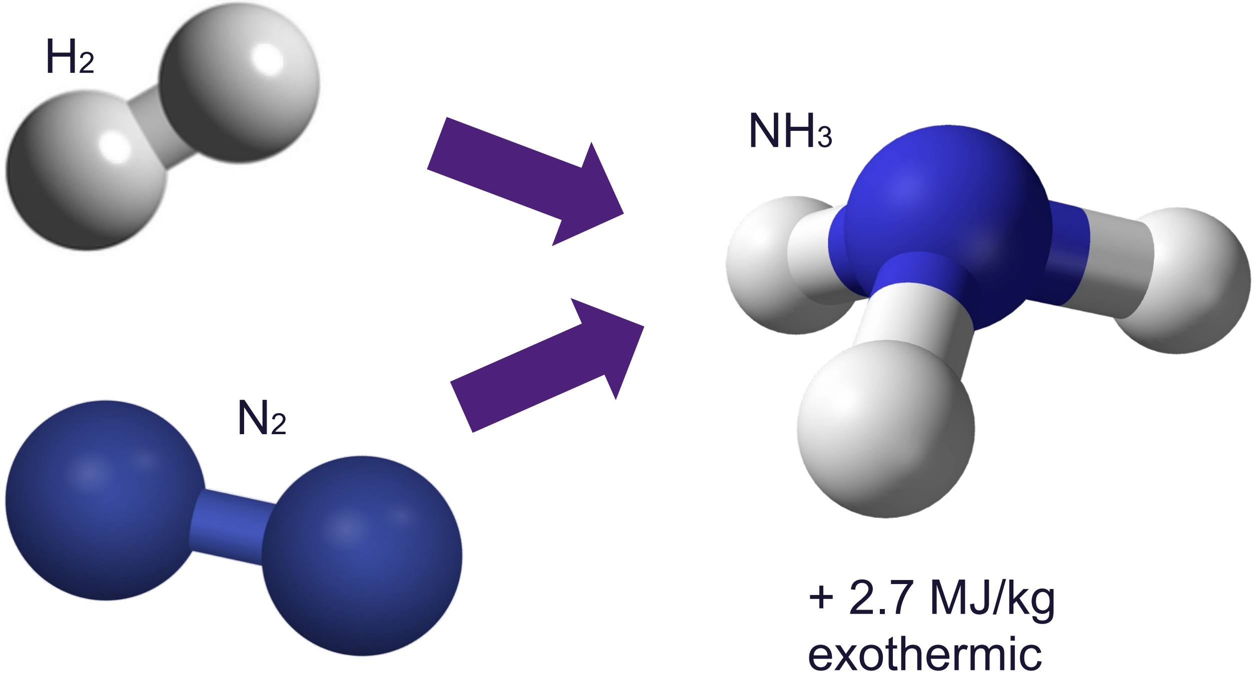
- NOx mostly formed as the fuel molecule is broken down in the process
- At some point a single N-atom will be there
    - It must not meet oxygen!

Implications for ammonia combustion

- Must burn in an oxygen depleted environment
- Ammonia has a low heating value and flame temperature -> not so prone to form thermal NOx as CH4, H2, etc
- Rich-lean staging can work
- Non-premixed (conventional systems) must be revisited

From H2 to NH3…

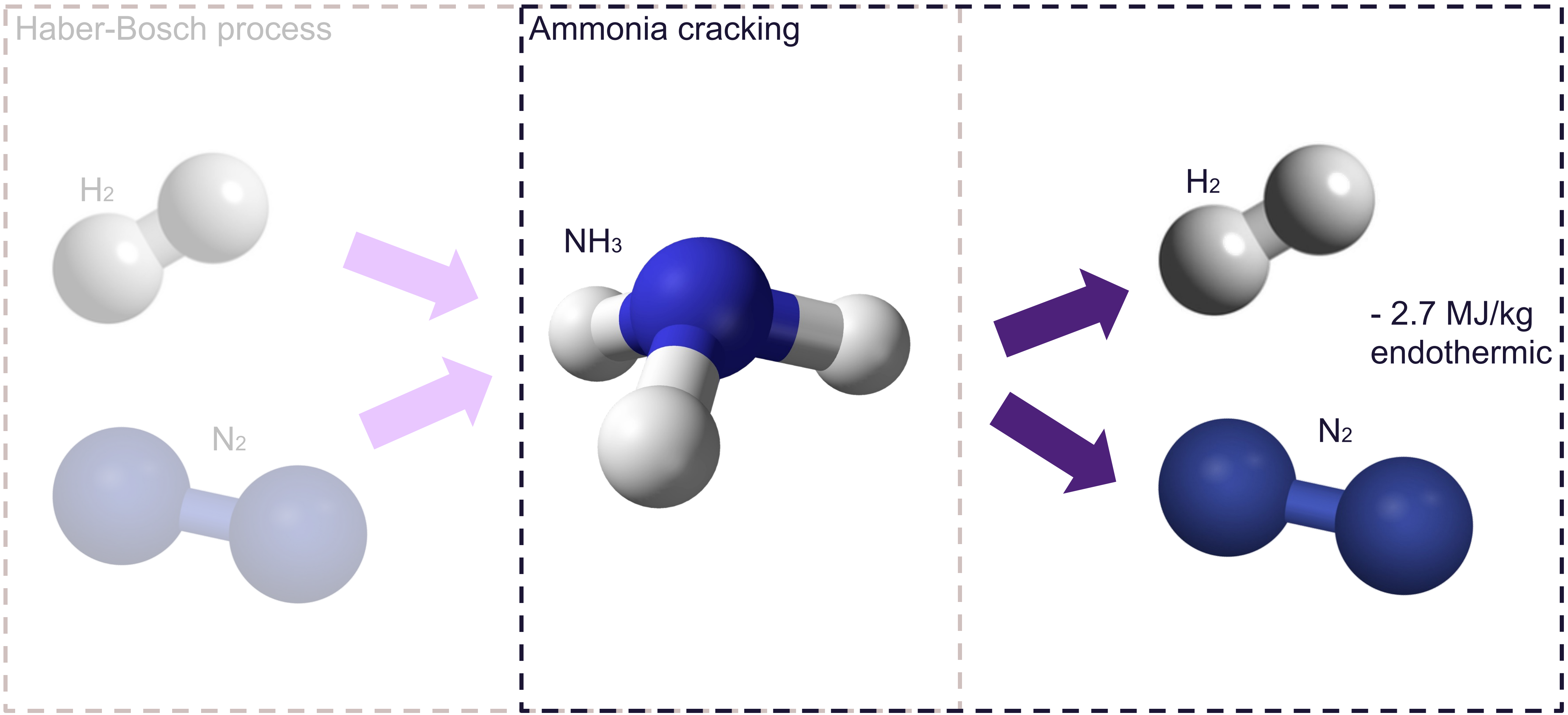
Haber-Bosch process



+ 2.7 MJ/kg
exothermic

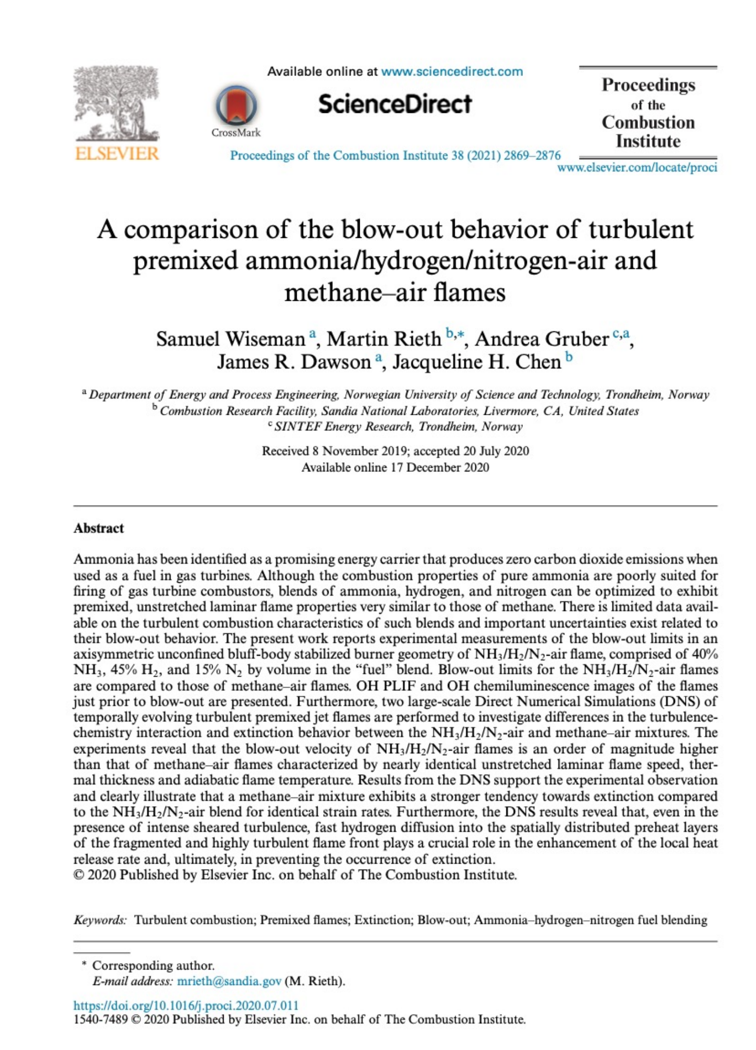
Siemens Energy is a registered trademark licensed by Siemens AG.

From H2 to NH3… and back again!



Siemens Energy is a registered trademark licensed by Siemens AG.

Turbulent $NH_3/H_2/N_2$–air flames blow-out



Available online at www.sciencedirect.com

ScienceDirect

ELSEVIER

CrossMark

Proceedings of the Combustion Institute 38 (2021) 2869–2876

Proceedings of the Combustion Institute

www.elsevier.com/locate/proci

A comparison of the blow-out behavior of turbulent premixed ammonia/hydrogen/nitrogen-air and methane–air flames

Samuel Wiseman [a], Martin Rieth [b,*], Andrea Gruber [c,a], James R. Dawson [a], Jacqueline H. Chen [b]

[a] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[b] Combustion Research Facility, Sandia National Laboratories, Livermore, CA, United States
[c] SINTEF Energy Research, Trondheim, Norway

Received 8 November 2019; accepted 20 July 2020
Available online 17 December 2020

Abstract

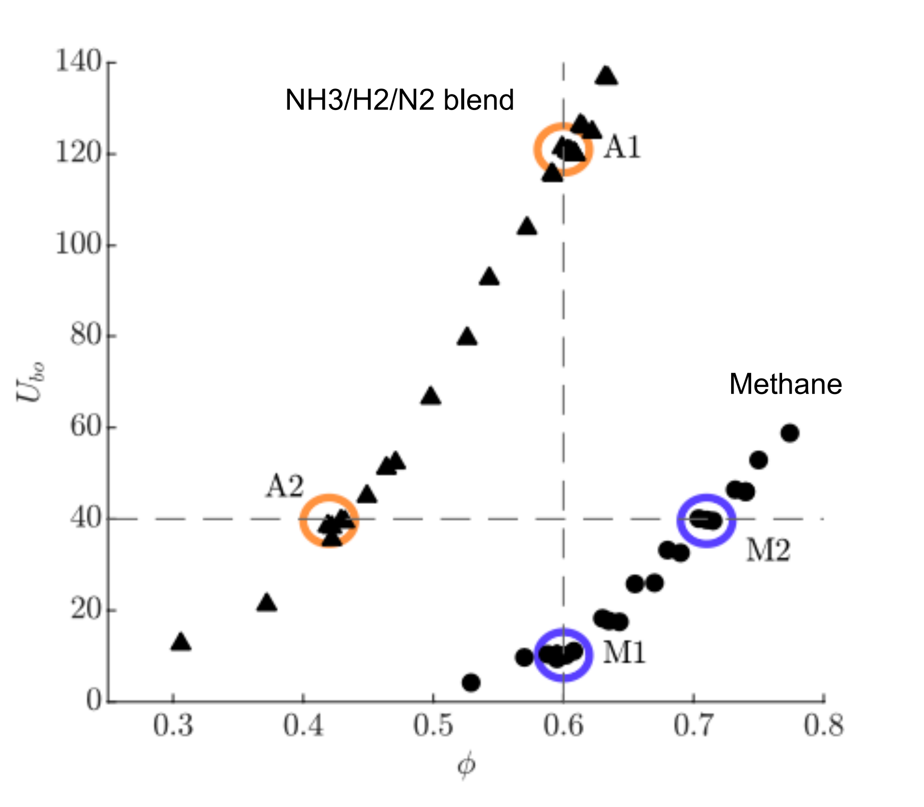
Ammonia has been identified as a promising energy carrier that produces zero carbon dioxide emissions when used as a fuel in gas turbines. Although the combustion properties of pure ammonia are poorly suited for firing of gas turbine combustors, blends of ammonia, hydrogen, and nitrogen can be optimized to exhibit premixed, unstretched laminar flame properties very similar to those of methane. There is limited data available on the turbulent combustion characteristics of such blends and important uncertainties exist related to their blow-out behavior. The present work reports experimental measurements of the blow-out limits in an axisymmetric unconfined bluff-body stabilized burner geometry of $NH_3/H_2/N_2$-air flame, comprised of 40% NH_3, 45% H_2, and 15% N_2 by volume in the "fuel" blend. Blow-out limits for the $NH_3/H_2/N_2$-air flames are compared to those of methane–air flames. OH PLIF and OH chemiluminescence images of the flames just prior to blow-out are presented. Furthermore, two large-scale Direct Numerical Simulations (DNS) of temporally evolving turbulent premixed jet flames are performed to investigate differences in the turbulence-chemistry interaction and extinction behavior between the $NH_3/H_2/N_2$-air and methane–air mixtures. The experiments reveal that the blow-out velocity of $NH_3/H_2/N_2$-air flames is an order of magnitude higher than that of methane–air flames characterized by nearly identical unstretched laminar flame speed, thermal thickness and adiabatic flame temperature. Results from the DNS support the experimental observation and clearly illustrate that a methane–air mixture exhibits a stronger tendency towards extinction compared to the $NH_3/H_2/N_2$-air blend for identical strain rates. Furthermore, the DNS results reveal that, even in the presence of intense sheared turbulence, fast hydrogen diffusion into the spatially distributed preheat layers of the fragmented and highly turbulent flame front plays a crucial role in the enhancement of the local heat release rate and, ultimately, in preventing the occurrence of extinction.

© 2020 Published by Elsevier Inc. on behalf of The Combustion Institute.

Keywords: Turbulent combustion; Premixed flames; Extinction; Blow-out; Ammonia–hydrogen–nitrogen fuel blending

* Corresponding author.
E-mail address: mrieth@sandia.gov (M. Rieth).

https://doi.org/10.1016/j.proci.2020.07.011
1540-7489 © 2020 Published by Elsevier Inc. on behalf of The Combustion Institute.



Experimental investigation of H_2/NH_3 flames at 1 atm

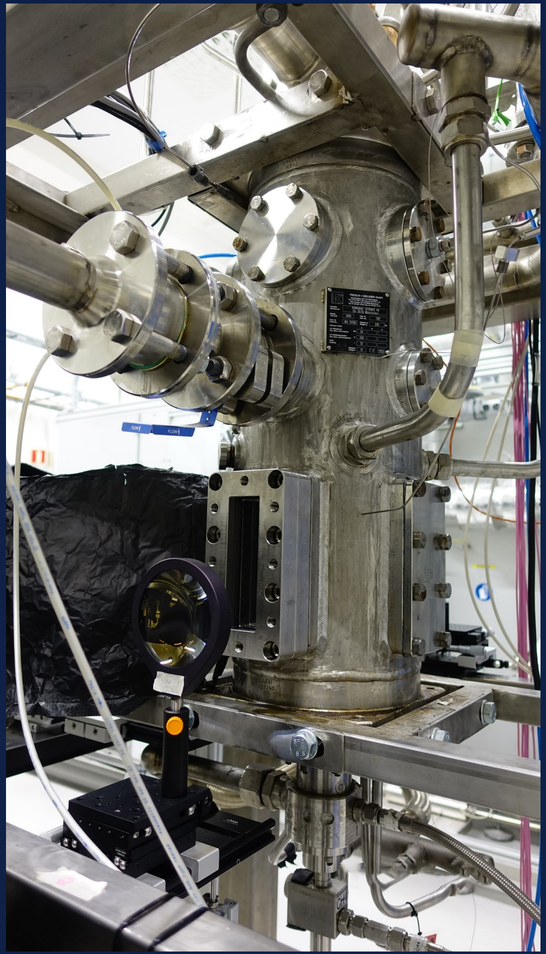
- Aim is to assess blow-out resilience in turbulent flames that are relevant to GTs

- Even stronger resilience to strain is observed in *turbulent* $NH_3/H_2/N_2$–air flames…
- …10-fold increase vs methane-air flames!!!

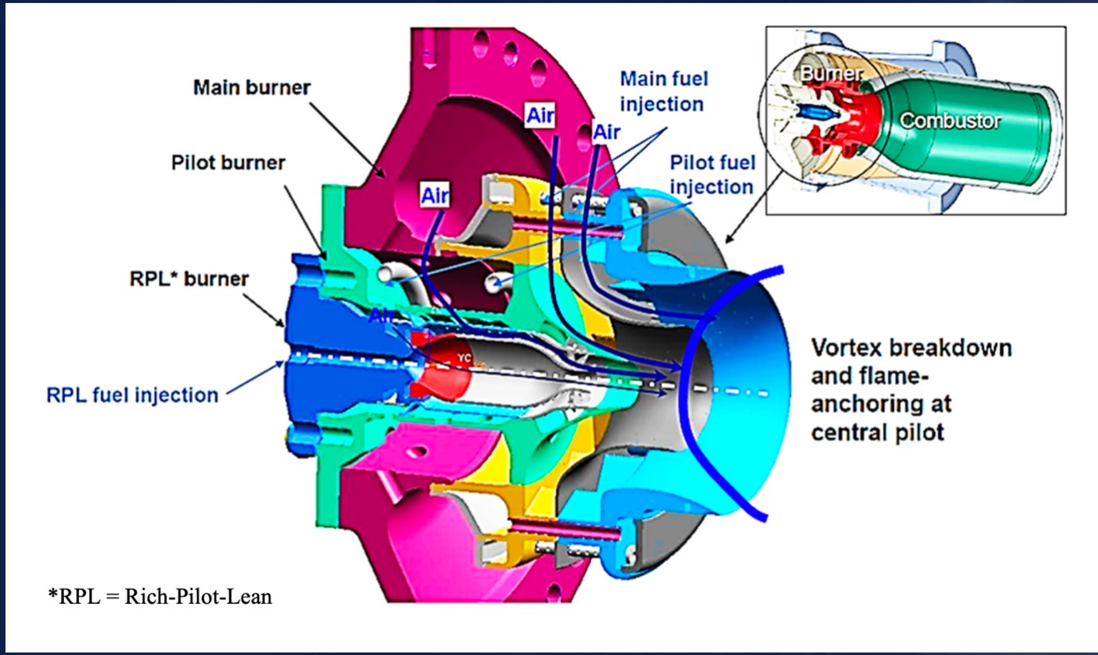
SINTEF NTNU

*Wiseman et al, "A comparison of the blow-out behaviour of turbulent premixed ammonia/hydrogen/nitrogen-air and methane-air flames", Proc Comb Inst vol 38, pp. 2869-2876 (2021)

HP-testing of scaled SGT750 burner



← SINTEF's HIPROX rig

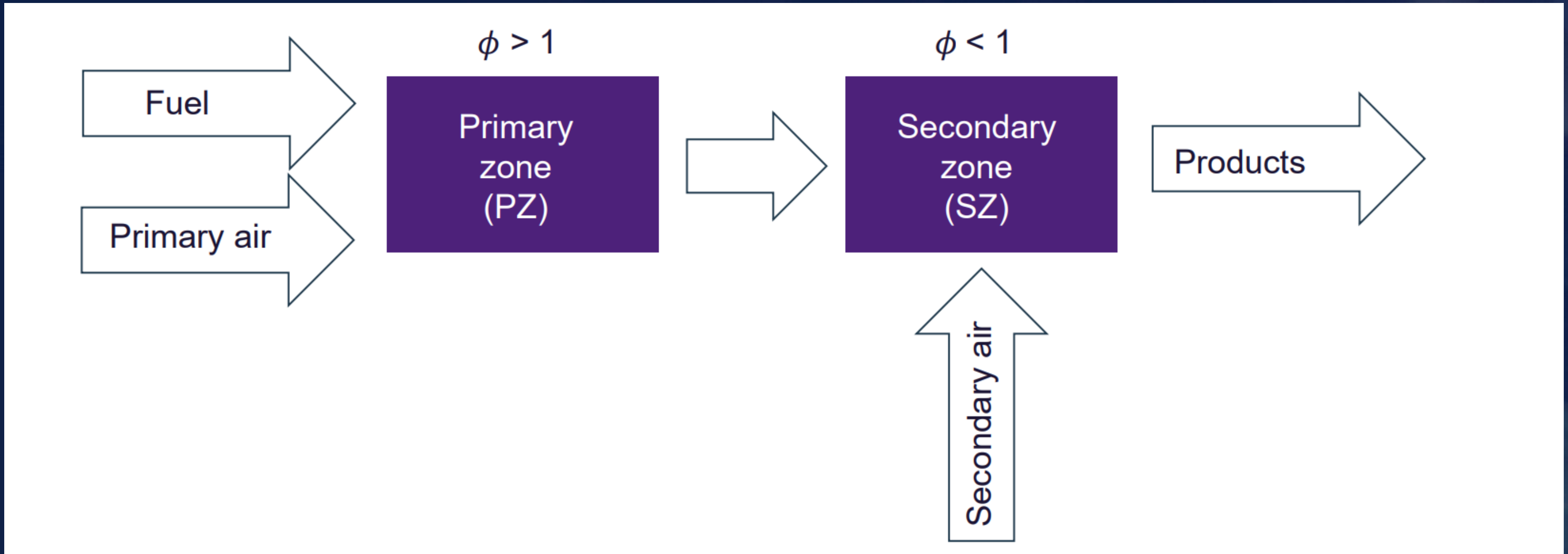


Siemens' 4th Gen DLE burner
(from A. Kundu, PhD thesis, Lund University)

Experimental investigation of H_2/NH_3 flame stabilization in scaled gas turbine combustor up to 10 atm

- Aim is to assess and demonstrate the viability of $NH_3/H_2/N_2$ blends as gas turbine fuel (stable flame / low emissions)

Rich-lean staged combustion



Rich-lean staging and high pressure

Proceedings of ASME Turbo Expo 2021
Turbomachinery Technical Conference and Exposition
GT2021
June 7-11, 2021, Virtual, Online

GT2021-60057

EXPERIMENTAL STUDY ON HIGH PRESSURE COMBUSTION OF DECOMPOSED AMMONIA: HOW CAN AMMONIA BE BEST USED IN A GAS TURBINE?

Mario Ditaranto
SINTEF Energy
Research AS
Trondheim, Norway

Inge Saanum
SINTEF Energy
Research AS
Trondheim, Norway

Jenny Larfeldt
Siemens Energy AB
Finspång, Sweden

ABSTRACT

Hydrogen, a carbon-free fuel, is a challenging gas to transport and store, but that can be solved by producing ammonia, a worldwide commonly distributed chemical. Ideally, ammonia should be used directly on site as a fuel, but it has many combustion shortcomings, with a very low reactivity and a high propensity to generate NOx. Alternatively, ammonia could be decomposed back to a mixture of hydrogen and nitrogen which has better combustion properties, but at the expense of an endothermal reaction. Between these two options, a trade off could be a partial decomposition where the end use fuel is a mixture of ammonia, hydrogen, and nitrogen. We present an experimental study aiming at finding optimal NH_3-H_2-*N2 fuel blends to be used in gas turbines and provide manufacturers with guidelines for their use in retrofit and new combustion applications. The industrial burner considered in this study is a small-scale Siemens burner used in the SGT-750 gas turbine, tested in the SINTEF high pressure combustion facility. The overall behaviour of the burner in terms of stability and emissions is characterized as a function of fuel mixtures corresponding to partial and full decomposition of ammonia. It is found that when ammonia is present in the fuel, the NOx emissions although high can be limited if the primary flame zone is operated fuel rich. Increasing pressure has shown to have a strong and favourable effect on NOx formation. When ammonia is fully decomposed to 75%* H_2 *and 25% N2, the opposite behaviour is observed. In conclusion, either low rate or full decomposition are found to be the better options.*

Keywords: Combustion, Ammonia, Hydrogen, NOx

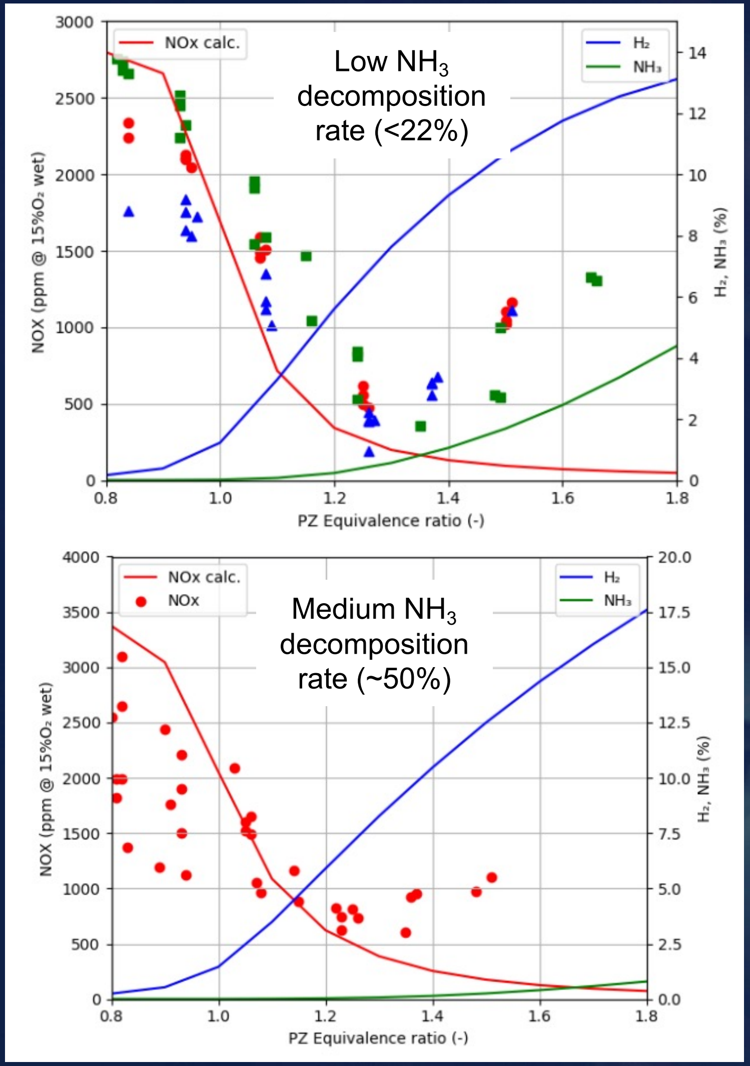
NOMENCLATURE

DCR	(Ammonia) Decomposition rate
Main	Main fuel section of the burner
R+P	RPL and Pilot fuel sections of the burner
PZ	Combustor primary zone
ER	Equivalence ratio

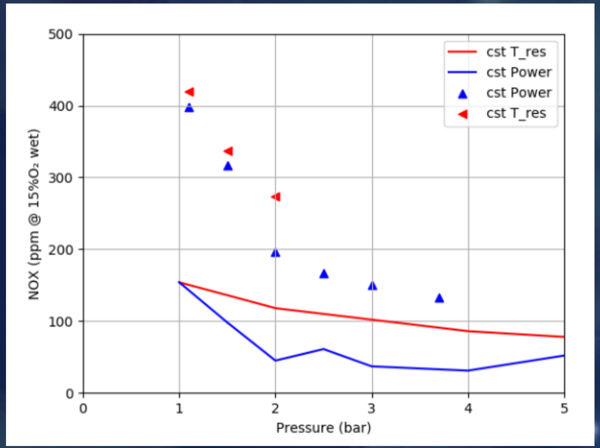
1. INTRODUCTION

Hydrogen is a carbon free fuel that has long been recognized as the fuel of the future. Unfortunately, that future has struggled to materialize due to several factors. One of them being that hydrogen is not naturally found on Earth and must be produced by a chemical or electrochemical process at an energetical cost considerably higher than that of natural gas extraction and production. The other issues are related to its physical properties. Hydrogen has a very low density, responsible for a low volumetric calorific value, which causes a problem for transport and storage requiring either very high pressure or large volume. This point is further aggravated by its high diffusivity and therefore potential for leakage. And leakages of hydrogen must be avoided at all costs because it is highly reactive with a wide flammability range in air. Transport and storage in liquid phase is therefore an interesting option, but it is also expensive as the vaporization point of hydrogen is at very low temperature. One solution is to transform hydrogen to ammonia [1] and transport it as a liquid, which is already distributed worldwide at very large scale by pipeline, rail, road, or ship. Some of the largest pipelines transport up to several million tonnes ammonia per year. The conventional Haber-Bosch process for producing ammonia is a

 © 2019 by ASME



Experimental investigation of H_2/NH_3 flame stabilization in scaled gas turbine combustor up to 10 atm



- Low-NO_x within reach using rich-lean fuel staging at high pressure!

SINTEF NTNU

*Ditaranto et al, "Experimental study on high pressure combustion of decomposed ammonia: how can ammonia be best used in a gas turbine?", ASME TurboExpo 2021

Learnings and preliminary recommendations

- High propensity to NOx even at low NH_3 content
- Pressure strongly affects conversion to NOx

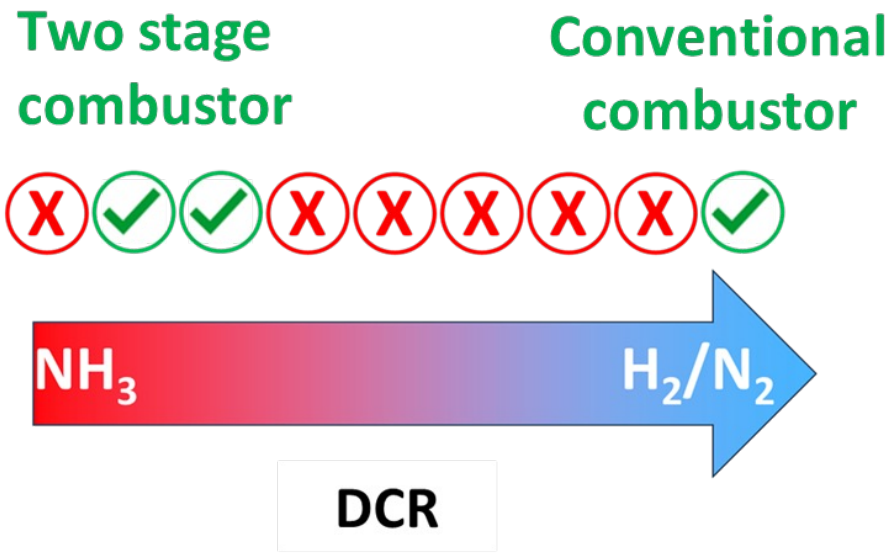
- **If lowest NH_3 DCR** is desired:

  Primary Zone optimal ER must be rich

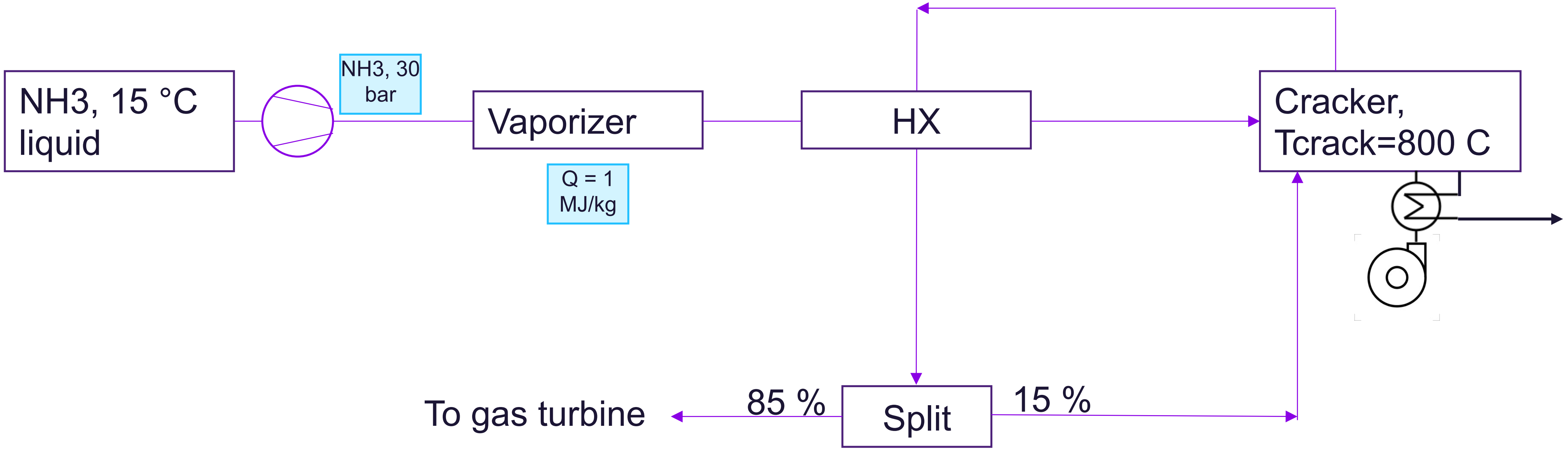
  Impact on GT combustor:

  - PZ must be rich
  - more air bypass
  - bigger and longer combustor

- **If lowest NOx emissions** is desired:
  - Decompose all!! But avoid NH_3 impurities
  - Impact on GT combustor:
    - Little

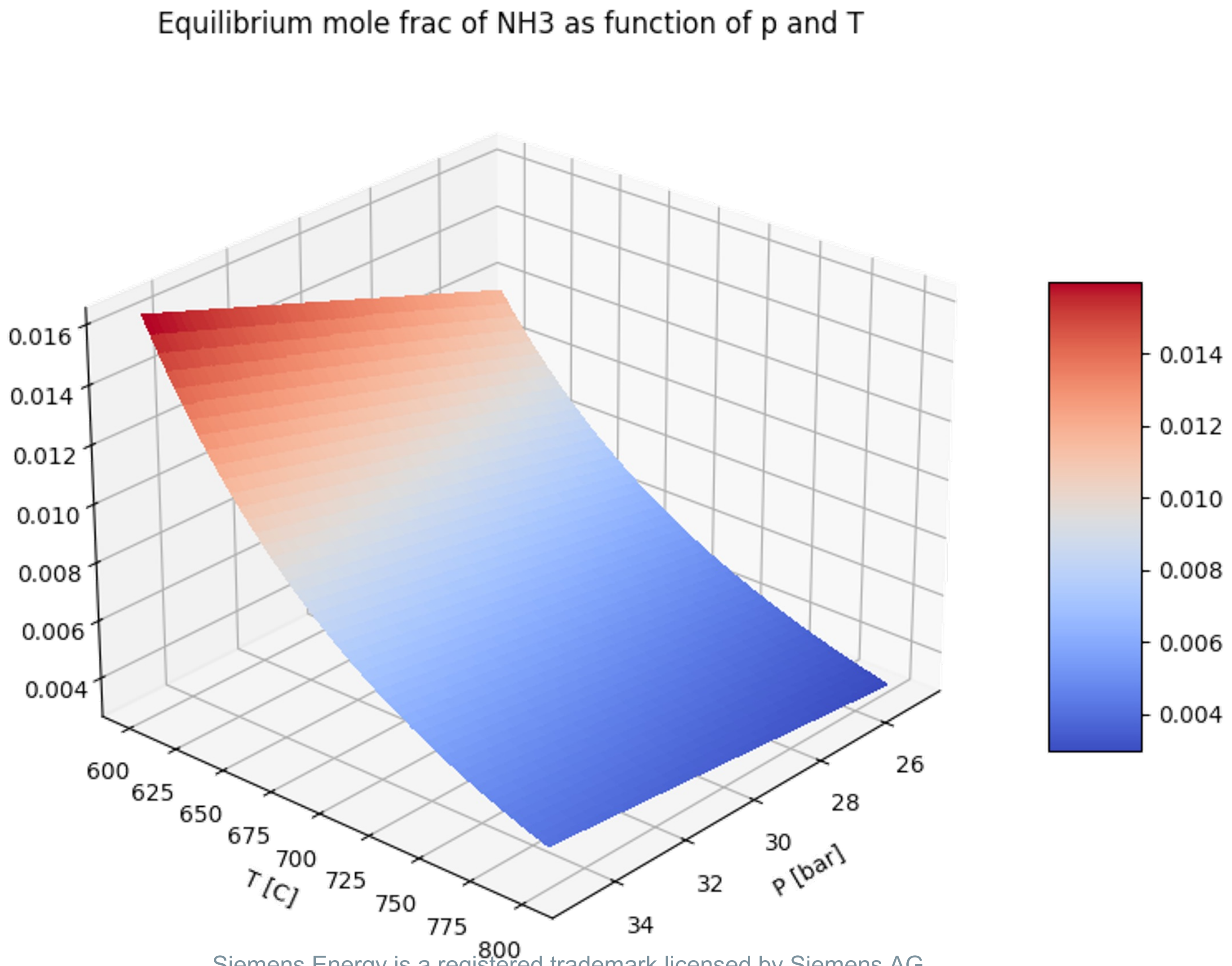


Simple layout for a cracker unit



Equilibrium of high temperature cracking

SIEMENS energy



Hence, we cannot get 100% cracked

At 0.5 vol-% NH_3 slip:

~1000 ppm NOx at "*100% NH3 to NO conversion*"

This is the absolute worst case – we expect lower. Testing will come!

SCR probably needed.

Siemens Energy is a registered trademark licensed by Siemens AG.