Pure ammonia operation in pre-chamber equipped medium-duty reciprocating engines

Prof. Will Northrop

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Collaborators

Funding

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H_2-based fuels, mostly ammonia, can play a key role in agriculture

Sector	2020	2030	2050
Total production hydrogen-based fuels (Mt)	**87**	**212**	**528**
Low-carbon hydrogen production	9	150	520
share of fossil-based with CCUS	*95%*	*46%*	*38%*
share of electrolysis-based	*5%*	*54%*	*62%*
Merchant production	15	127	414
Onsite production	73	85	114
Total consumption hydrogen-based fuels (Mt)	**87**	**212**	**528**
Electricity	0	52	102
of which hydrogen	0	43	88
of which ammonia	0	8	13
Refineries	36	25	8
Buildings and agriculture	0	17	23
Transport	0	25	207
of which hydrogen	0	11	106
of which ammonia	0	8	44
of which synthetic fuels	0	5	56
Industry	51	93	187

https://www.iea.org/reports/net-zero-by-2050

Ammonia can be produced locally, increasing the **resilience** and **independence** of agriculture

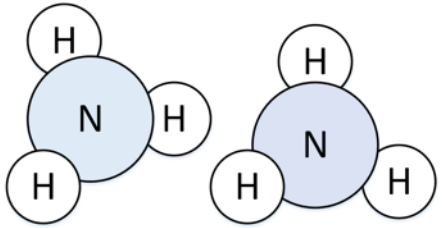
Stranded wind resources

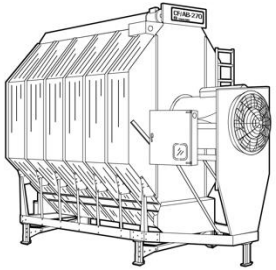
Local ammonia production

Fertilizer

Fuel

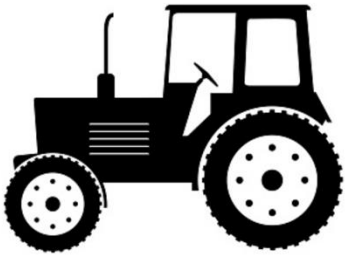
Ammonia is a carbon-free fuel that can be combusted in **existing** agricultural energy systems





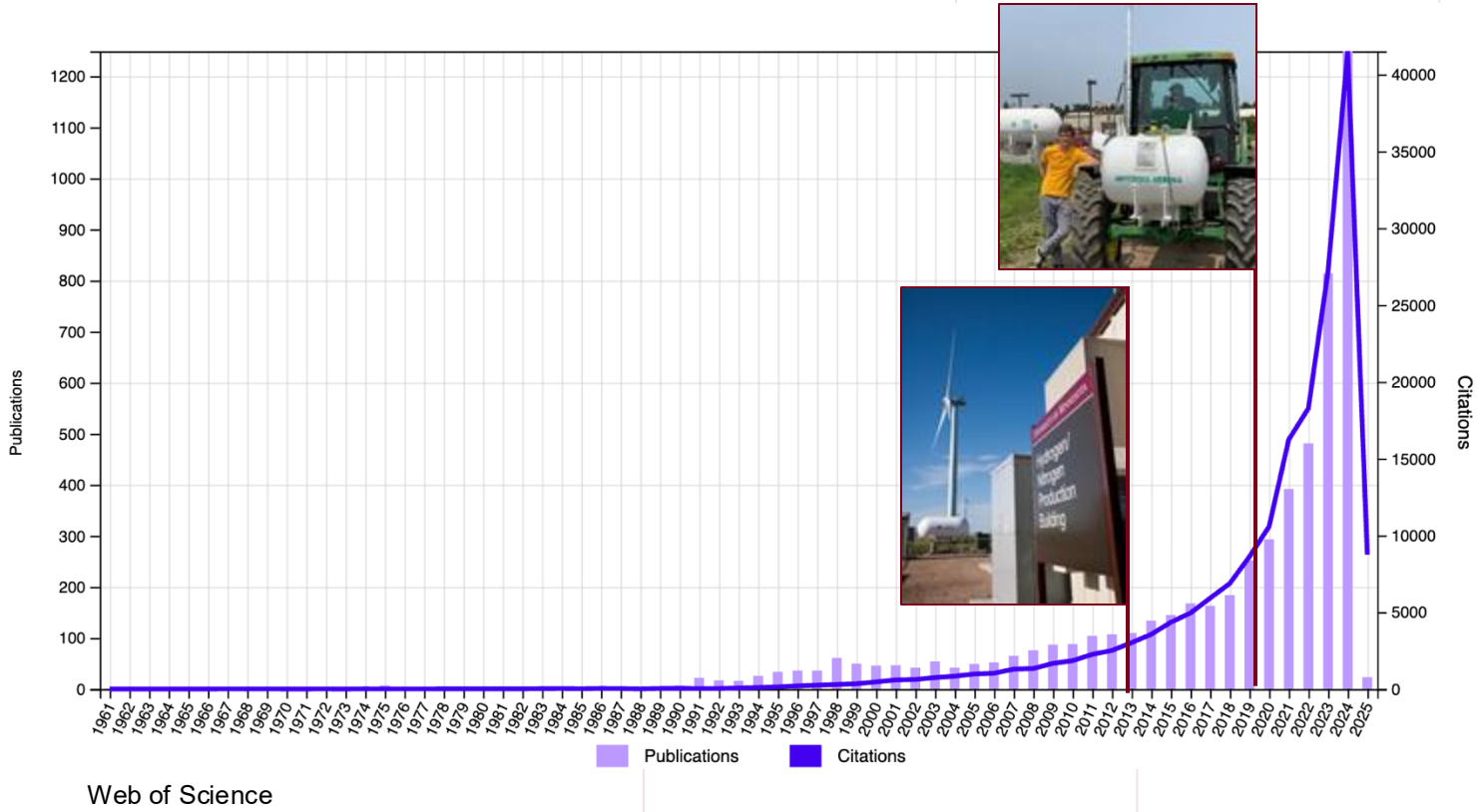
Grain Drying

Power Generation



Ag Equipment

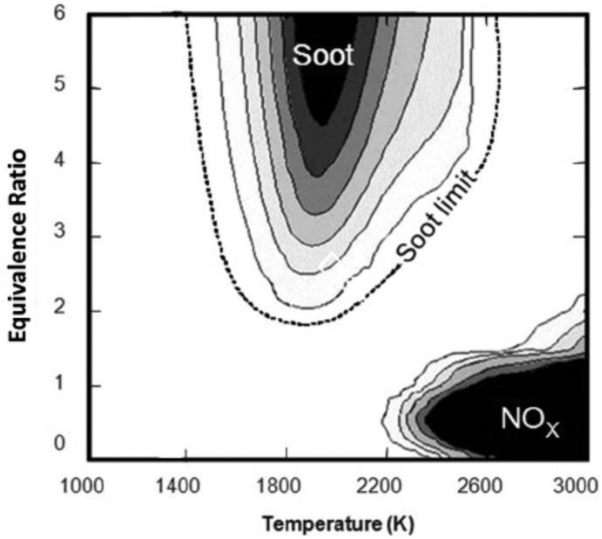
“ammonia combustion” citation report captures exponentially growing global research interest



Web of Science

Motivation: Regimes of nitrogen species formation in an engine in a ϕ-T domain

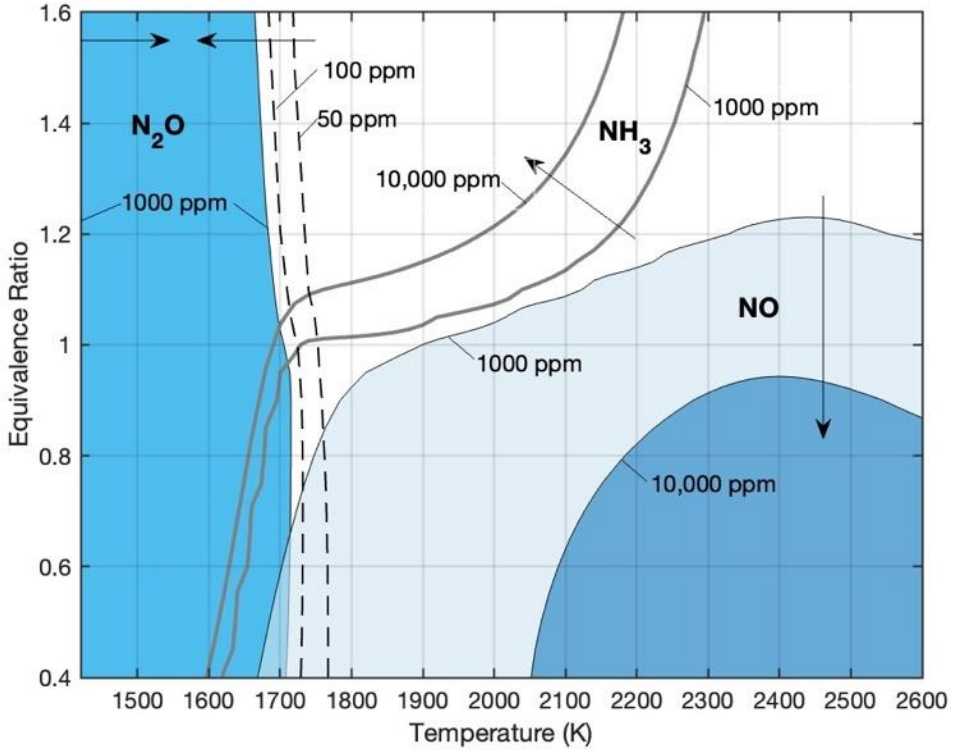
- Ammonia SI or dual fuel CI engine occurs over a constant equivalence ratio, but varying spatio-temporal temperature
- View N-species formation from flame propagation through premixed charge in local ϕ -T space
- An analogous plot can be created for diesel combustion



Kamimoto T, Bae M. SAE 880423.
Akihama K, Takatori, Y, Inagaki K, Sasaki S, et. al. SAE 2001-01-0655.

Large islands of NO, unburned NH_3 and N_2O form at engine relevant pressure and timescales

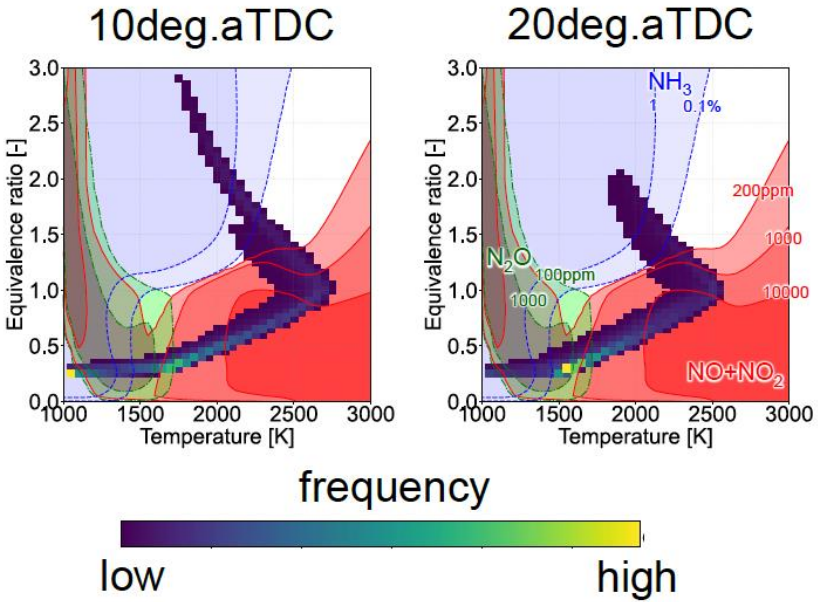
N_2O, NO, and NH_3 in ϕ-T space for ammonia combustion



O-D constant temperature/pressure reactor (no energy), Stagni Mechanism
P = 20 bar, $t_{residence}$ = 1 ms ~ 10 CAD at 1800 rpm

Northrop, W.F. (2024) Modeling nitrogen species from ammonia reciprocating engine combustion in temperature-equivalence ratio space. *Applications in Energy and Combustion Science*, 100245. https://doi.org/10.1016/j.jaecs.2023.100245

Challenge: For dual fuel or piloted engines, difficult to avoid all three N-species formation islands



- Dual fuel ammonia premixed
- Diesel fuel direct injection
- 57% ammonia by energy
- Global phi = 0.54

Implication: Lean dual fuel diffusion combustion will be challenged by N_2O formation in cold and lean regions of the flame.

Hiraoka K, Matsunaga D, Kamino T, Honda Y, et. al. Experimental and numerical analysis on combustion characteristics of ammonia and diesel dual fuel engine. SAE Technical Paper 2023:2023-32-0102. https://doi.org/10.4271/2023-32-0102.

Objective: Use pre-chamber spark engine concepts to allow 100% ammonia operation over full operating range with diesel-like performance

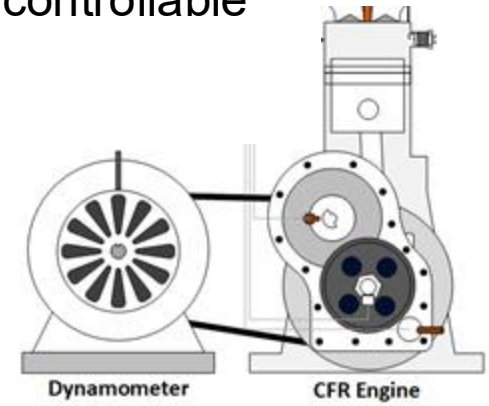
Pre-chamber Advantages:

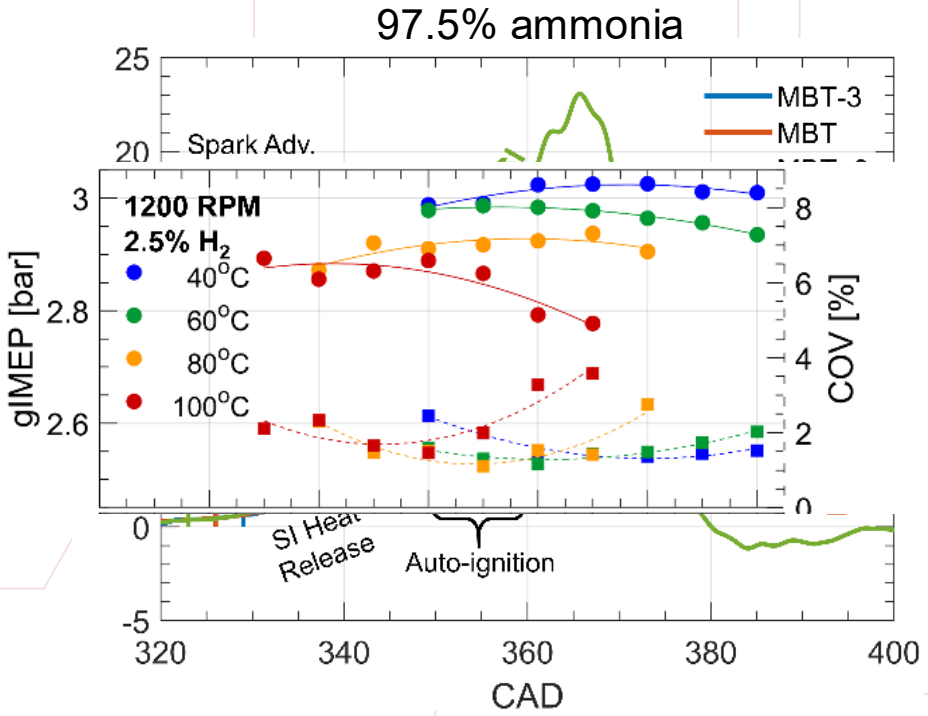
- Premixed charge (for passive)
- Distributed ignition sites
- Increased turbulence
- Extended lean limit
- No need for hydrogen addition
- Fully carbon-free without a pilot fuel

https://www.mahle-powertrain.com/en/experience/mahle-jet-ignition/

Spark-assisted compression ignition (SACI), a possible solution for enabling stable engine combustion

- Shortened combustion duration possible with SACI
- High coefficient of variation (COV) – not controllable

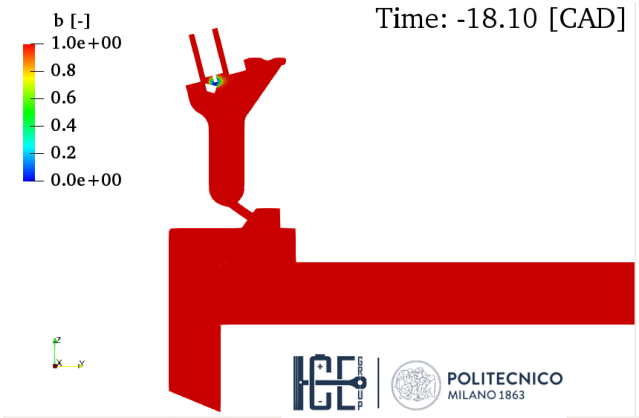


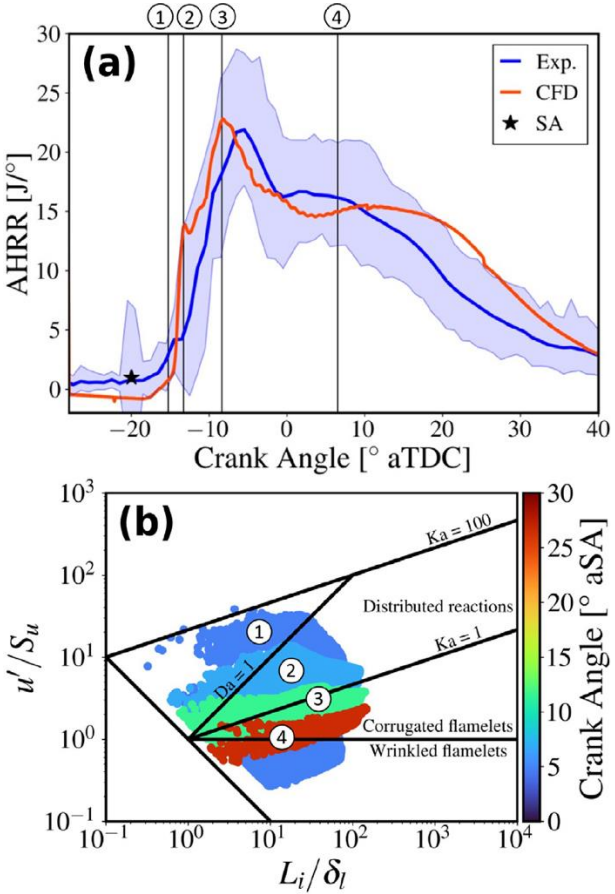


Reggeti, S., Kane, S., & Northrop, W. (2023). Experimental Investigation of Spark-Assisted Compression-Ignition with Ammonia-Hydrogen Blends. *Journal of Ammonia Energy*, *1*(1). DOI: https://doi.org/10.18573/jae.21

Turbulent jet ignition can shorten ignition delay: Active pre-chamber with 2.5% H_2 injection

CFR Engine 18:1 Compression Ratio





Sforza, Lorenzo, Shawn Reggeti, Alessandro Nodi, Federico Ramognino, Alessandro Stagni, Tommaso Lucchini, Gianluca D'Errico, and William Northrop. "Impact of hydrogen injection strategies on ammonia internal combustion engines ignited with active pre-chambers." *Fuel* 388 (2025): 134414.

Summary of Single Cylinder Pre-Chamber Engine Studies

- Single-cylinder Cummins 6.7 L platform developed to explore pre-chamber combustion for pure ammonia
- Passive pre-chamber promising for shortening combustion duration and increasing stability at light load
  - Engine operation over full speed and load range
  - 100% ammonia fueling
  - Larger pre-chamber volume leads to excessive rates of heat release
- NOx emissions remain flat over the load range for PC operation
  - NOx levels are adjustable with mixture control
- N_2O emissions also do not increase with decreasing load, the same as with spark; increase when lean

Upcoming Publications

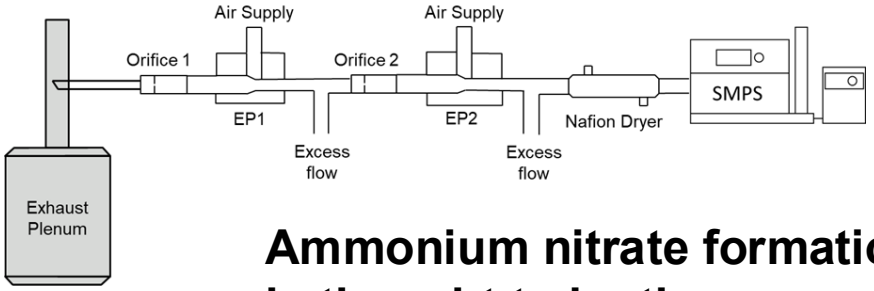
Dhotre, A., Voris, A. Northrop, W.F. (accepted) Comparison of spark and turbulent jet ignition in a fully ammonia-fueled engine, *SAE PF&L*

Voris, A., Kane, S., Okey, N, Northrop, W.F. (in review) Pre-Chamber Combustion of Pure Ammonia in a Single-Cylinder Medium-Duty Engine, *ASME ICEF 2025.*

Voris, A., Kane, S., Okey, N, Northrop, W.F. (in review) Full Operational Map of a Spark-Ignited Medium-Duty Single-Cylinder 100% Ammonia-Fueled Engine, *International Journal of Engine Research*.

Ammonia combustion emits no soot, but there still particles

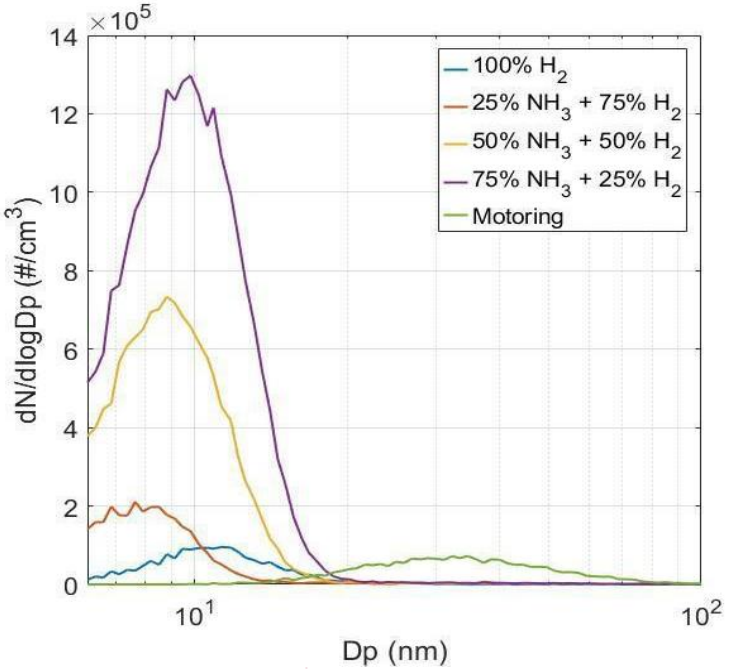
Sampling system – CFR engine



Ammonium nitrate formation is thought to be the cause

$$2\,NO_2 + 2\,NH_3 \rightarrow N_2 + H_2O + NH_4NO_3$$

$$NH_4NO_3 \leftrightharpoons NH_3 + HNO_3$$



Patil, Tejashri, et al. "Experimental Investigation of Particulate Emissions From An Ammonia-Fueled Internal Combustion Engine." *Journal of Engineering for Gas Turbines and Power* 147.10 (2025): 101014.

Summary of Ammonium Nitrate Particle Sampling Experiments

- Particles measured from Cummins single-cylinder engine
  - Deposited on 37 mm aluminum foil and Teflon filter substrates
  - Characterized for composition using ATR-FTIR, Raman Spectroscopy, TEM imaging, and STEM-EDS mapping
- Higher than motoring condition particle mass found in ammonia combustion samples based on SMPS measurements
- Raman spectroscopy and TEM imaging confirm that the particles are AN
- Ash metals found with the particles raise questions about the formation mechanism (homogeneous vs. heterogeneous)
- Future work includes laminar flame sampling, plug-flow reactor studies, and kinetics.

Upcoming Publication

Patil, Tejashri, Northrop W.F. (in review) Ammonium Nitrate Nanoparticle Emissions from Ammonia-Fueled Internal Combustion Engines *J. Aero Sci.*

Summary

Ammonia can be an effective hydrogen carrier for off-highway ground vehicles like in agriculture where it is also a fertilizer

Passive pre-chamber allows diesel-like performance in engines for pure ammonia fueling over full load range

Full operating range is possible with relatively flat N-species emissions, controllable with phi

NO_X will be controllable, N_2O is a key challenge, and ammonium nitrate particulate emissions exist

2025 Ammonia Energy Symposium!

https://soae.umn.edu/

YOUR INSIGHTS & QUESTIONS WELCOMED

Q&A

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