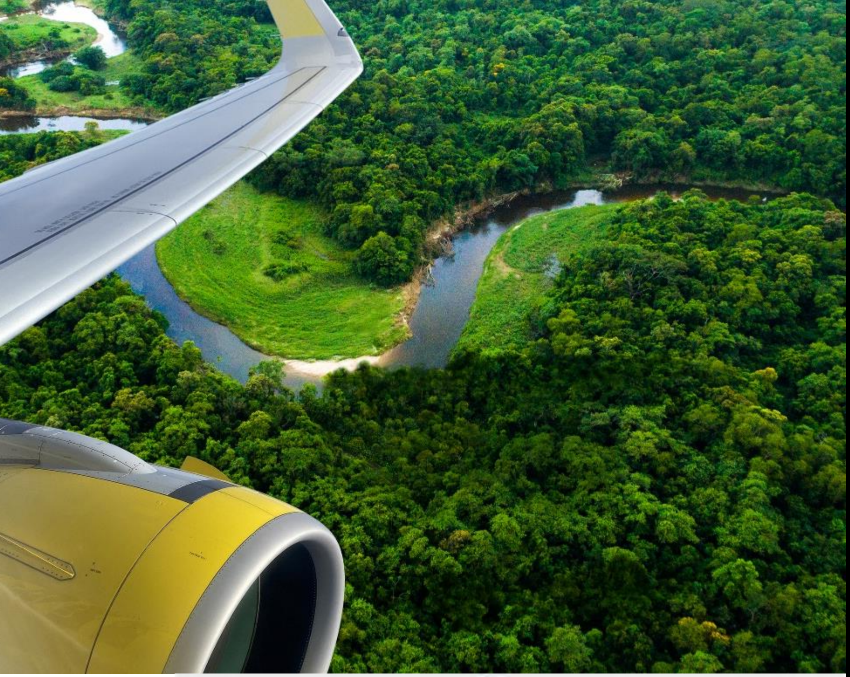

Carbon-Free Fuels in Gas Turbines, for Propulsion & Power

FT4000® Aeroderivative Dual Fuel Gas Turbine Engine.

RTX

COLLINS AEROSPACE | PRATT & WHITNEY | RAYTHEON

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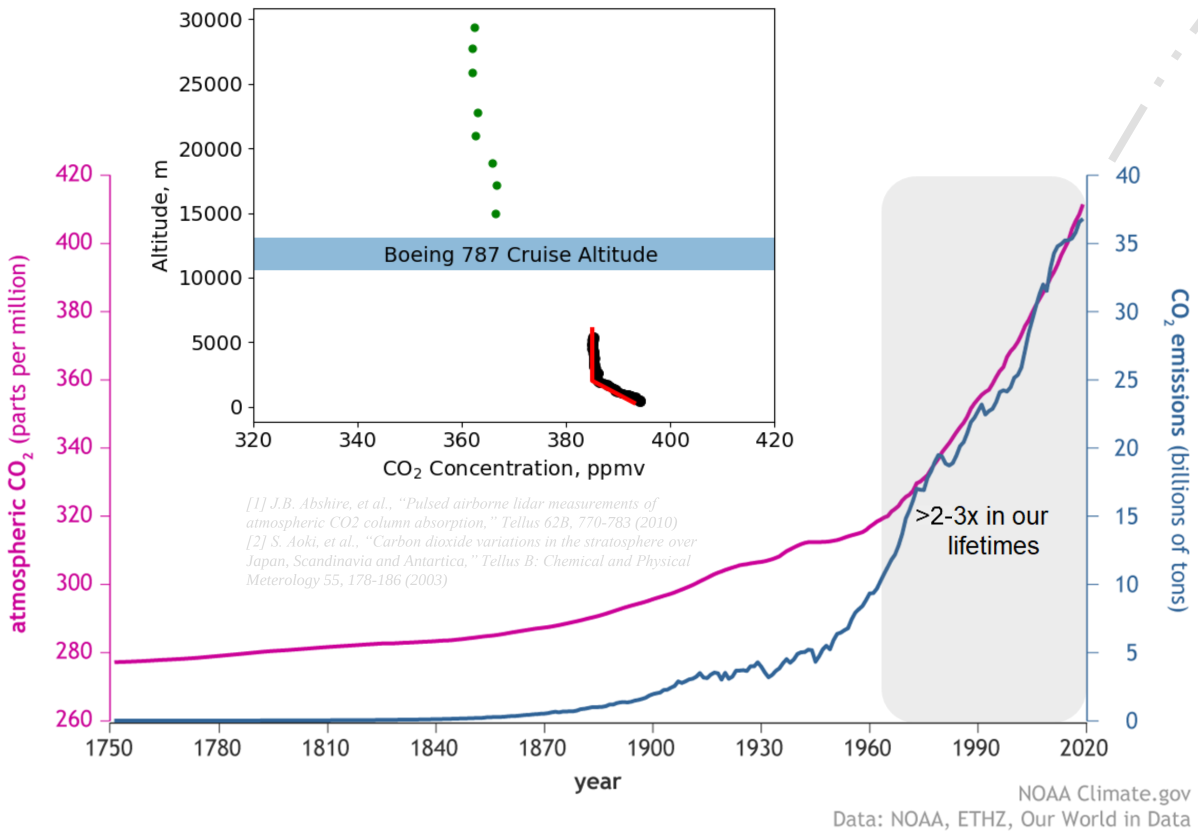
Lance Smith
RTX Technology Research Center

Carbon-Free Fuel Combustion Workshop
Boston, MA, 16 March 2025
14th US National Combustion Meeting (USNCM)

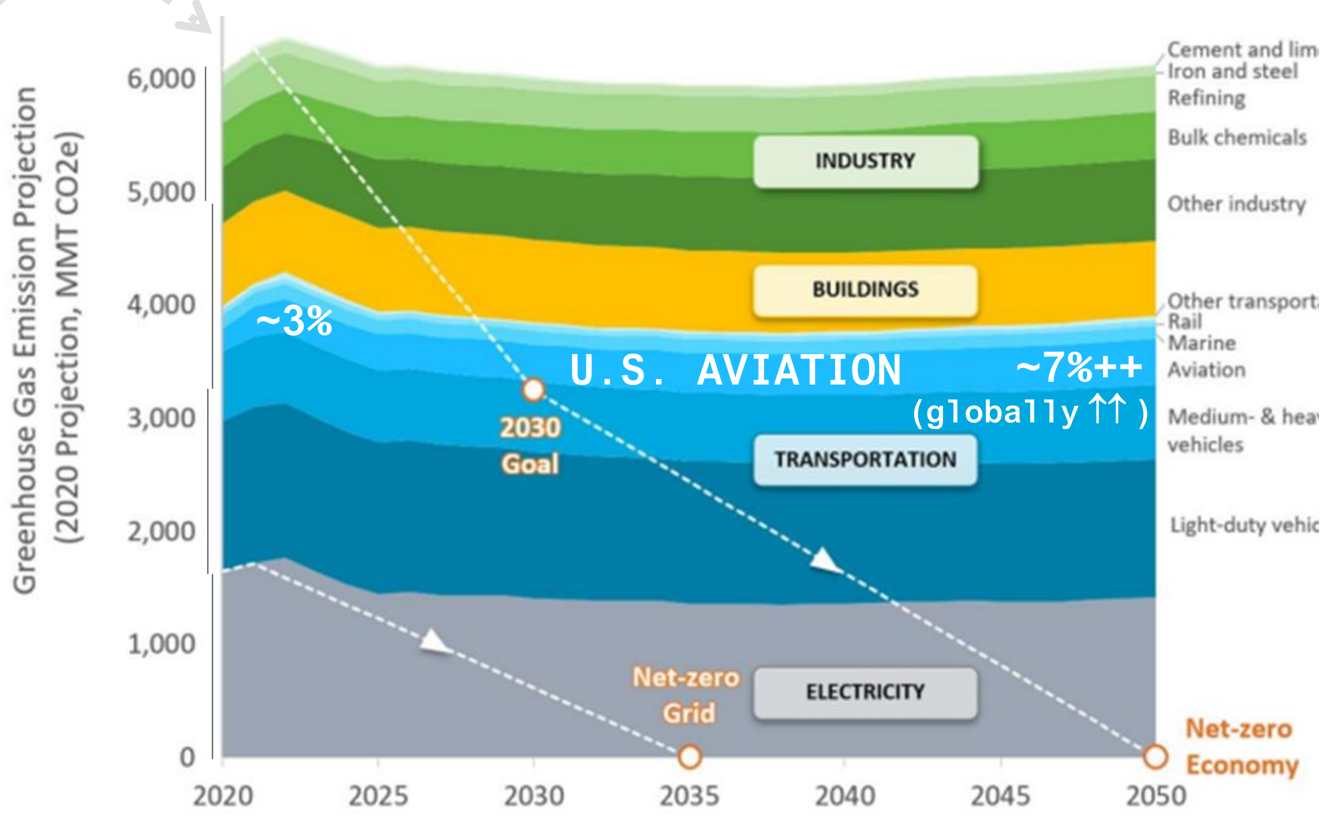
Approved for public release. © 2025 RTX.

Context: Gas Turbines' Contribution to CO_2 Emissions

NOAA climate data:



DOE energy projections & roadmapping:



www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

Gas Turbine Power

- **Aviation contributes ~3%+++ of anthropogenic CO_2 emissions** …… in US & Globally ……
- **Aviation is challenging to de-carbonize → long service life & "energy dense" power needed**
- ➢ **Power generation Gas Turbines contribute + ~10% CO_2 emissions in US**
- ➢ **Shipping CO_2 emissions similar level as Aviation globally: fewer GTs but more fuel-flexible**

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https://www.eia.gov/todayinenergy/detail.php?id=61444

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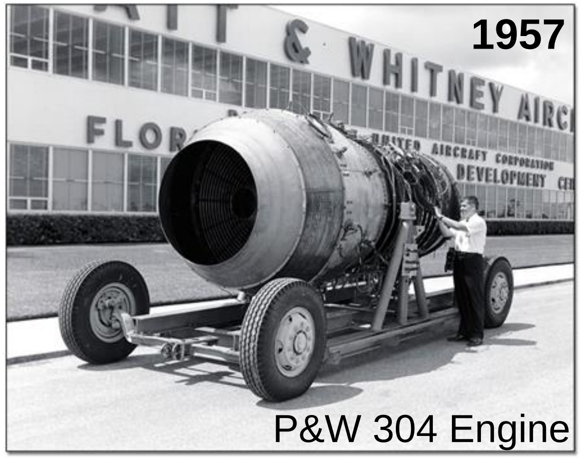
Hydrogen-based Engines (incl. NH_3) … *re-visit for new (& old) reasons*

Early Cold-War Era:

- ***high-altitude, high-speed flight***

NASA X-15

➢ *NH_3 fueled rocket engine*

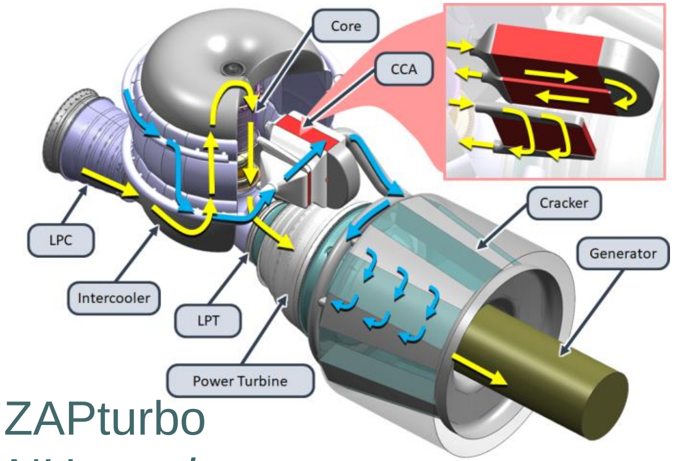


Project Suntan

➢ *H_2 turbine engine, predecessor to RL10 rocket engine*

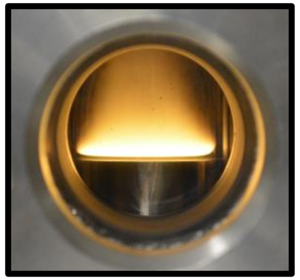
Climate-Change Era:

- ***low carbon, low climate-impact flight***



ZAPturbo

NH_3 engine concept



"LOAD-Z" DOE

NH_3 combustion studies

HySIITE *H_2 engine concept*

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RAYTHEON

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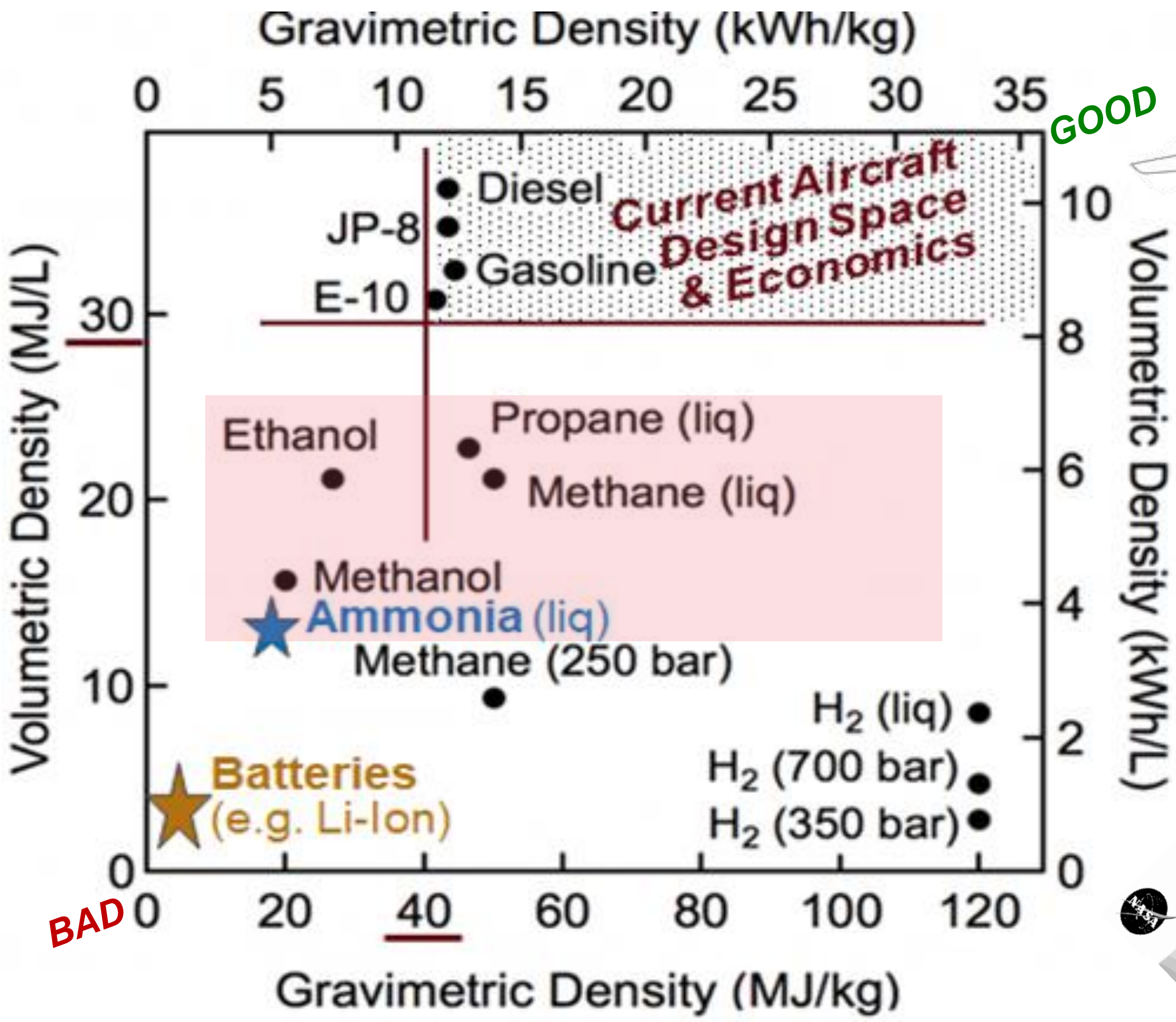
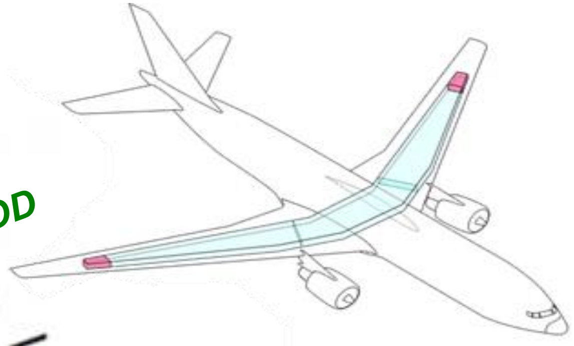
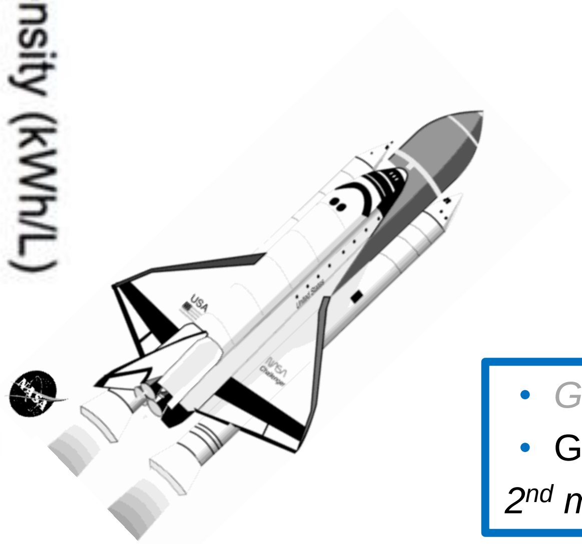
"Net-Zero Carbon" Fuel Options in Aviation: Volume & Weight

https://www.energy.gov/eere/fuelcells/hydrogen-storage







- **Hydrogen**
- **Ammonia**
- "Low"-Carbon Fuels:
  - LNG
  - Methanol
- (Batteries)

> - *Global Jet fuel use ~200B kg/yr.*
> - Global NH_3 production ~175B kg/yr.
>
> *2nd most transported chemical in world*

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- **Ammonia's energy similar to Methanol; Storage properties similar to Propane → "familiar" fuel**

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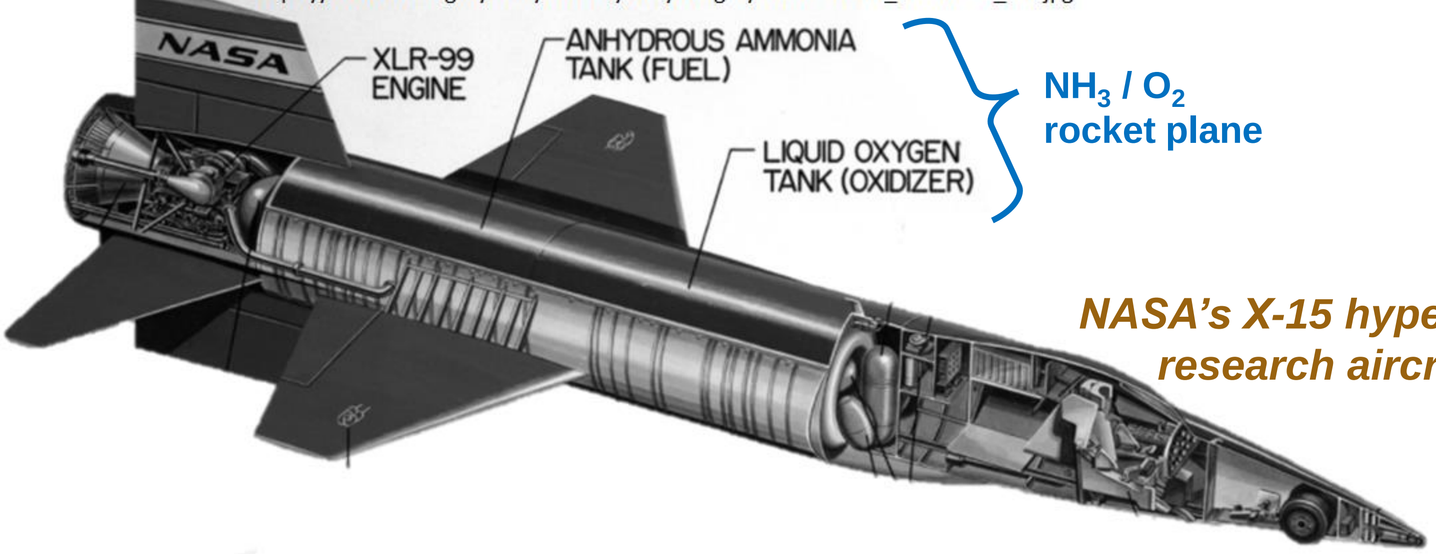
NH_3 as a useful propulsion fuel: How (or Why)

https://www.nasa.gov/sites/default/files/images/342156main_E62-7893_full.jpg



NH_3 / O_2 rocket plane

1960 … 1st flight of NH_3-powered aircraft

NASA's X-15 hypersonic research aircraft

XLR-99 rocket engine:
propellant = NH_3 / LOx

WHY?

- NH_3 chemically stable
- NH_3 easily liquefied *(-33C)*
- NH_3 has excellent properties for nozzle cooling *-- better cooling & thrust than ethanol/water, & pre-dates RP-1 & LH_2 developments*
- NH_3 does not coke → ***Able to absorb significant heat***

And has zero carbon!

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Ammonia propulsion is viable, & has been demonstrated in flight

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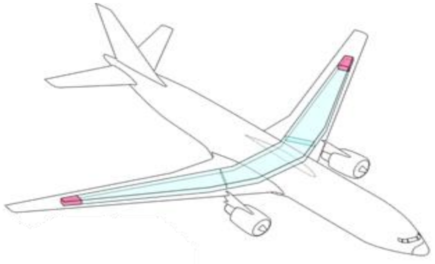
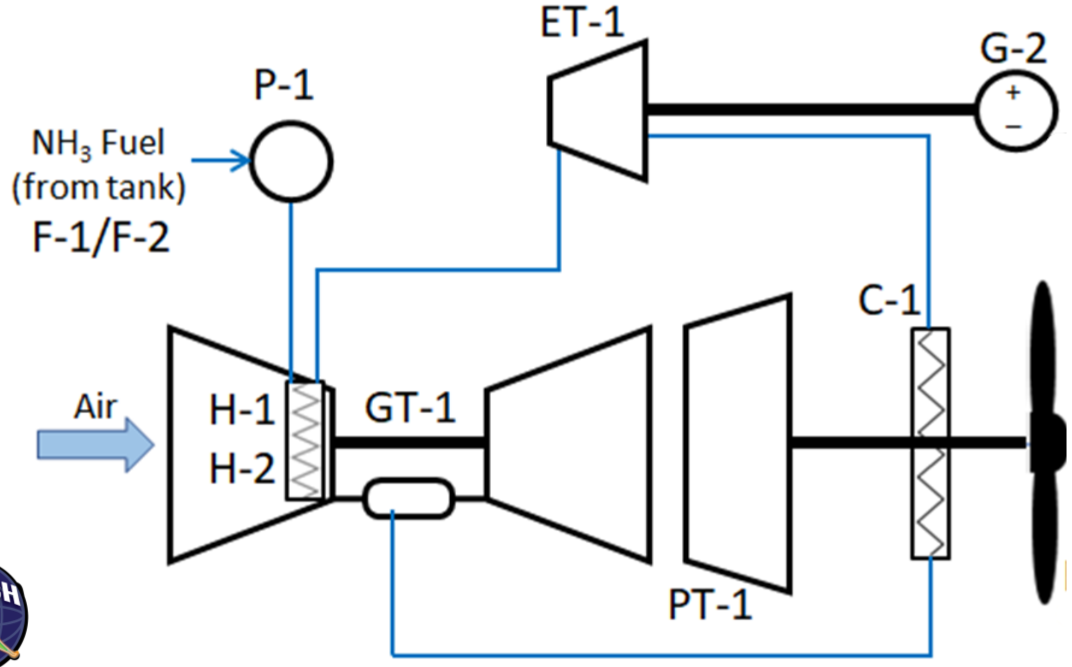
Beyond Storage: Fuel Properties for Cooling & Working Fluid

Performance Metrics, for Low-Carbon Fuel Options		Units *w/LHV fuel energy (Lower Heat. Val.)*	**LH2** Liquid Hydrogen	**NH3** Anhydrous Ammonia	**Liquid CH4 / "eLNG"** *e.g. SpaceX, Blue Origin*	**SAF or Jet-A** *(state of art)*
Thermal & Thermodynamic Properties	Thermal Conductivity, k	W / m-K (liquid)	0.1	0.6	0.2	0.1
	Heat Capacity, Cp	kJ / kg-K (liquid)	**9.7**	**4.5**	**3.5**	2.0
	"Gamma" ratio, Cp/Cv	in gas state	1.4	1.3	1.3	< 1.05 (C8+)
	Heat of Vaporization, h_fg	kJ / kg	446	***1370***	510	350
	Heat of Cracking reaction	kJ / kg	N/A	***2700***	N/A	coking issues





- **Thermal energy captured in fuel goes to *top* of Brayton cycle when burned**
  - ➢ high-efficiency heat re-capture! *(recuperation effect)*
- **NH_3 *liquid* esp. useful as working fluid,** for i-cooling & in bottom. cycle
  - ➢ cycle opportunity for GTs using large cold-liquid storage:
    - aeroderivative power incl. ships
    - also note LNG opp.

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arpa·e
CHANGING WHAT'S POSSIBLE
ZAPturbo

REEACH

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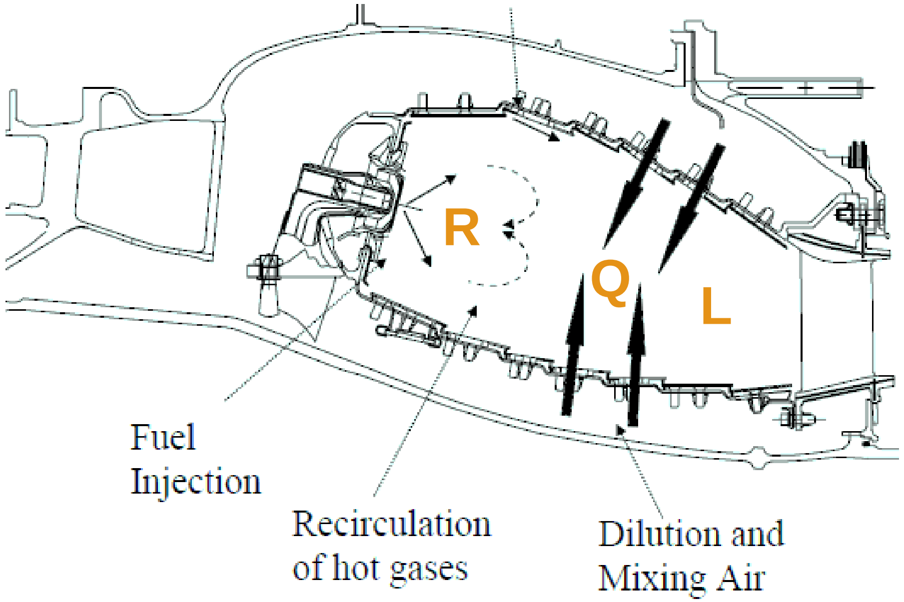
Challenge: How to Burn NH_3 with low NOx emissions ?

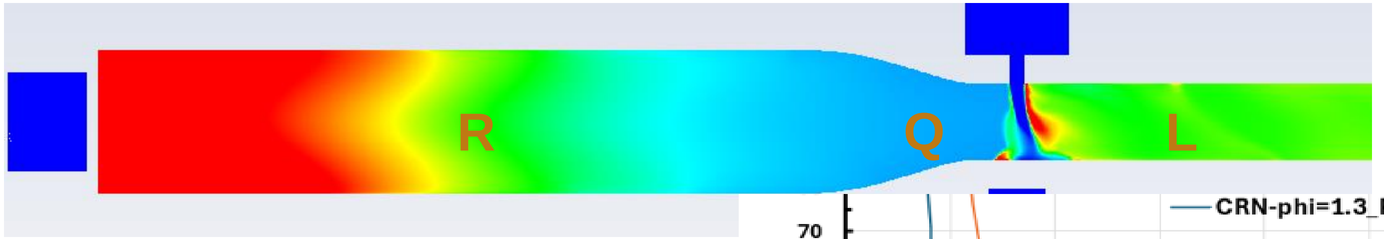
Re-think approach to RQL combustion…

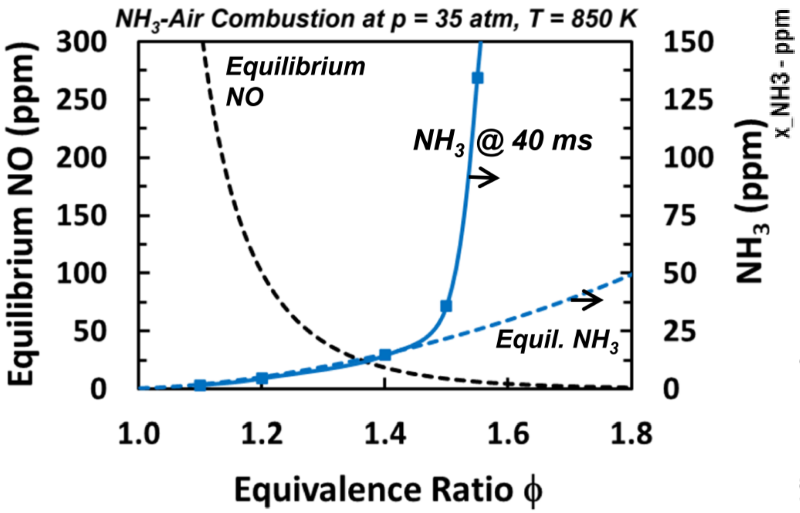
"Conventional" RQL, e.g. hydrocarbon fuels (NG, Jet…):

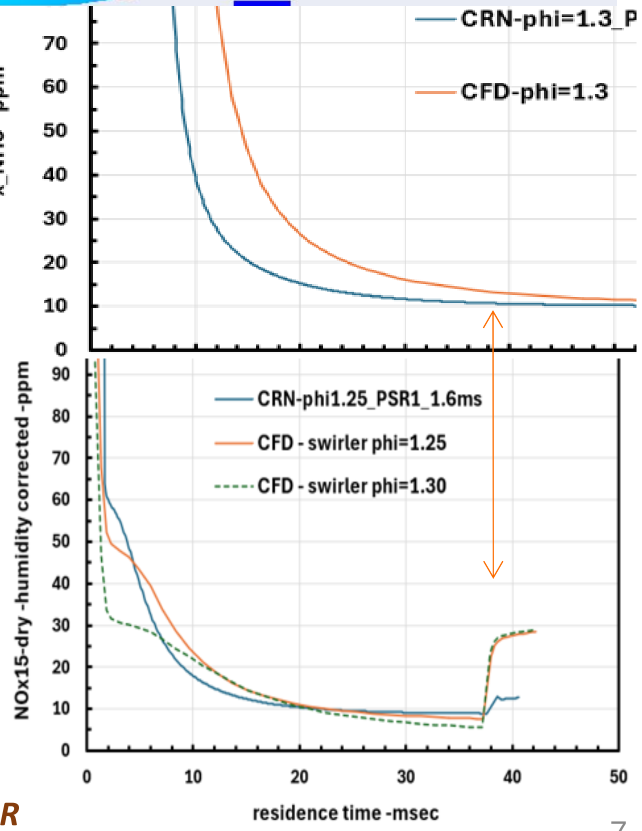


- Rich-zone considerations:
  - PM (soot) vs. turndown → FAR range
  - Ignition/stability → geom./size ($\tau_{AnchorZone}$)
- Lean-zone considerations:
  - CO burnout vs. NOx → τ_{Lean} ↑or↓, rapid mixing
  - PF (temp. uniform.) → complete mixing

Rich-Quench-Lean (RQL) *reconfigured* for low-NOx *NH_3 combustion*:







- New/Different considerations for NH_3:
  - Drive N-species to N_2 → τ_{Rich}↑↑
  - FAR_{RICH} determined by chem. equilib.
  - $NOx_{THERMAL}$↓ = rapid mixing ***w/less Q_{AIR}***

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DOE / NETL-sponsored project on NH_3 combustion studies

Low-NOx Operable Ammonia-Combustor Development (LOAD-Z)

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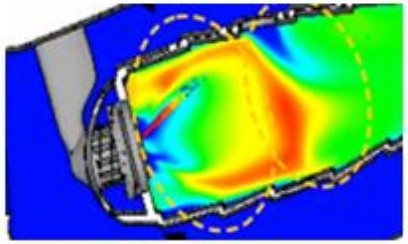
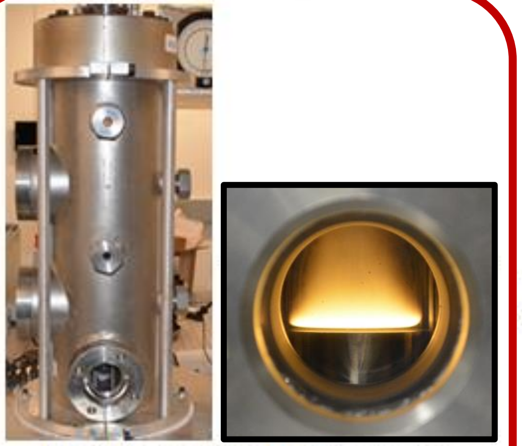
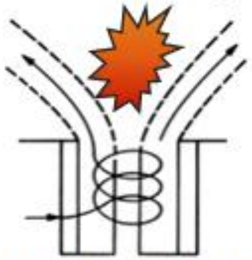
Year-4
Year-3
Year-2
Year-1
Time



- Single-nozzle high-pressure combustor, fired w/NH_3 fuel
- Measure emiss. & performance: NOx, efficiency, stability



- Flat-flame high-P burner (>>1-atm) for NOx eval.



- 1-atm swirl-stab. burner
- Piloting studies w/H_2

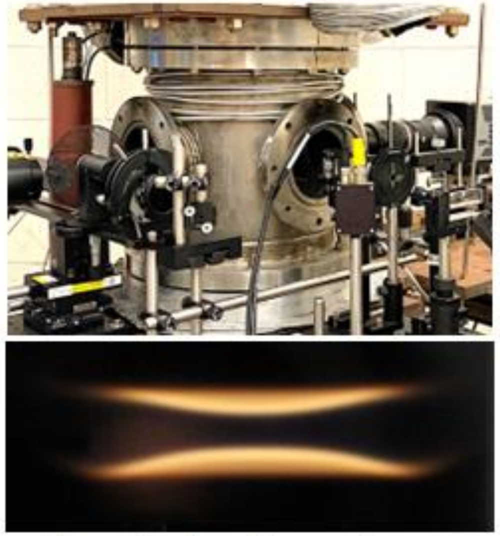
Modeling:

- CFD for design
- Kinetic improve. w/ exp. data

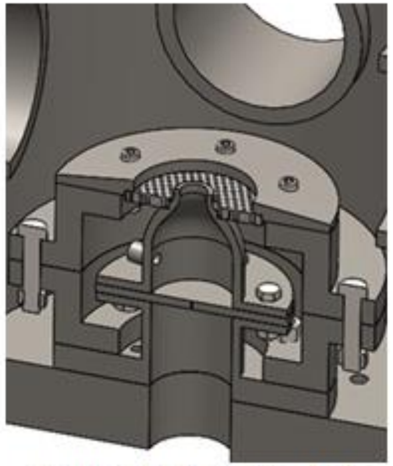
- CFD & validation
- Turb. models for NH3 comb. & NOx (no post-process.)

- CRN modeling
- Counterflow
- Kinetic mech.

UConn



- Counterflow flame rig, compatible w/NH_3 fuel
- Measure strained flames w/ inlet P, T > ambient



- Turbulent S_L rig, for NH_3 @ P, T > ambient (~20% turb. intensity)

Is it real?
(can we really get low-NOx NH_3 combustion)

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UNIVERSITY OF CONNECTICUT

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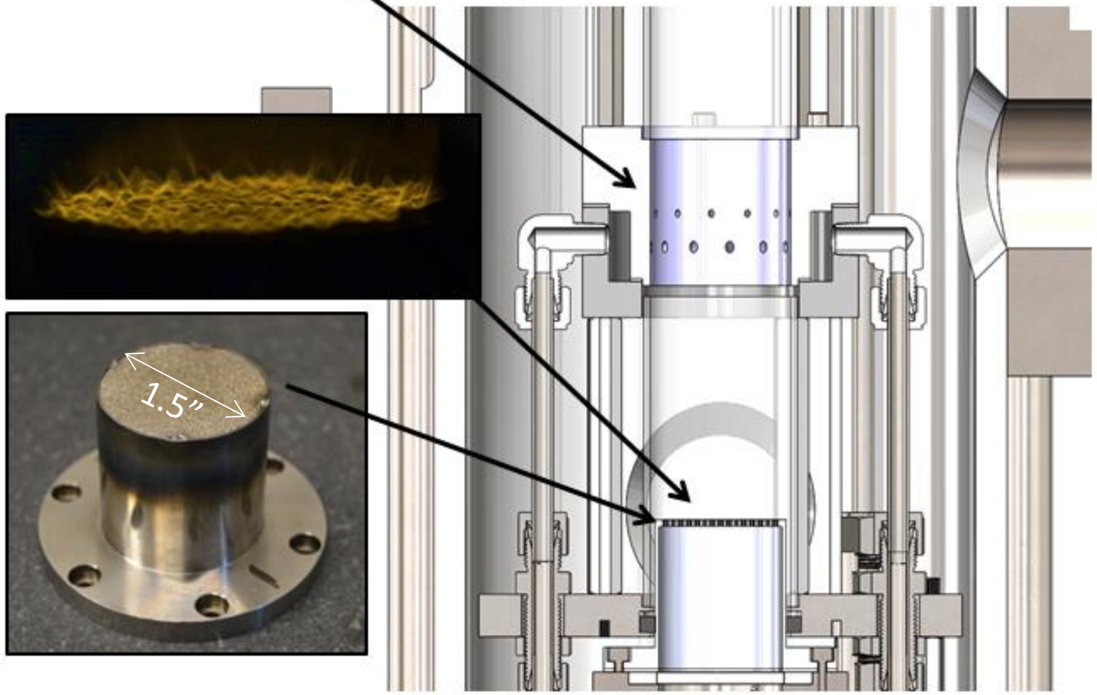
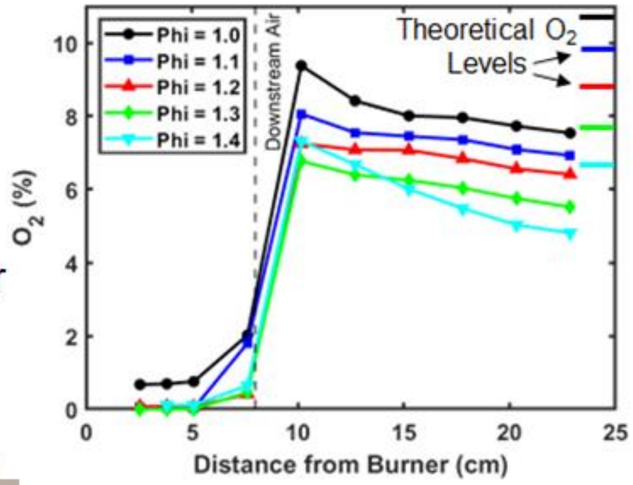
RTRC Lab Evaluation: Pure NH_3 combustion @ elevated P, T

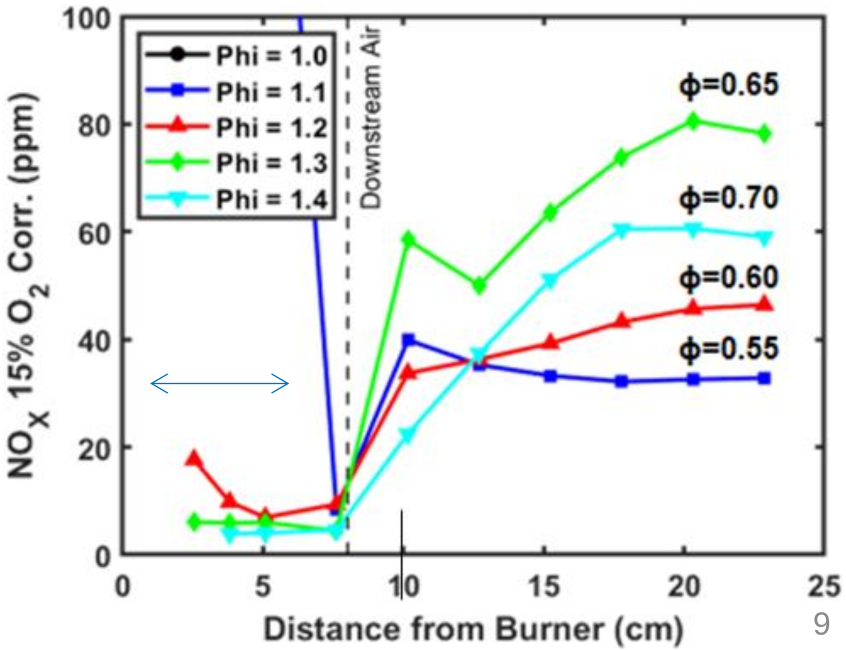
Preliminary data shows 35ppm NOx in 5-atm pressure RQL "burner"

Flat-Flame Burner Rig – Downstream Air Addition

- Data collected at **P = 5 atm**, **T_{in} = 450 K**
- Downstream air injection flowrate matched with burner air to allow for rich-to-lean transition (**50 / 50 airsplit**)
- Air injection ring located 8-cm downstream of burner







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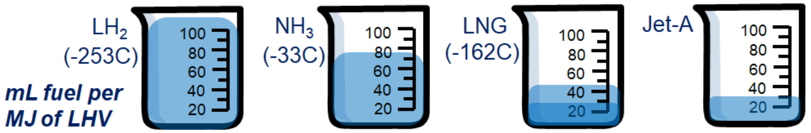
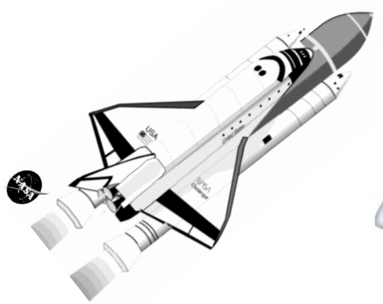
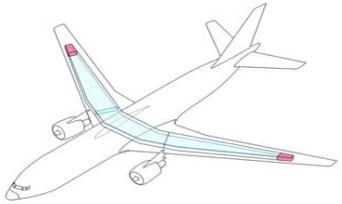
What about H2…: Storage Vol. & Temp.



Performance Metrics, for Low-Carbon Fuel Options		Units *w/LHV fuel energy (Lower Heat. Val.)*	LH2 Liquid Hydrogen	NH3 Anhydrous Ammonia	Liquid CH4 / "eLNG" *e.g. SpaceX, Blue Origin*	SAF or Jet-A *(state of art)*
Thermal & Thermodynamic Properties	Thermal Conductivity, k	W / m-K (liquid)	0.1	0.6	0.2	0.1
	Heat Capacity, Cp	kJ / kg-K (liquid)	**9.7**	**4.5**	**3.5**	2.0
	"Gamma" ratio, Cp/Cv	in gas state	1.4	1.3	1.3	< 1.05 (C8+)
	Heat of Vaporization, h_fg	kJ / kg	446	***1370***	510	350
	Heat of Cracking reaction	kJ / kg	N/A	***2700***	N/A	coking issues
Fuel Storage Requirements	Specific Energy	MJ / kg	**120**	**18.6**	**50**	43
	Energy Density of liquefied fuel	MJ / L	**8.5**	**12.7**	**21.1**	34
	Tank conditions	°C (K) atm	–253 °C (20 K) 1 atm	–33 °C (240 K) 1 atm	–162 °C (111 K) 1 atm	ambient



RTO-EN-AVT-150



Hydrogen Storage Challenge:
Seek Opportunities for Efficiency

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science.nasa.gov/science-news/science-at-nasa/2007/04may_methaneblast

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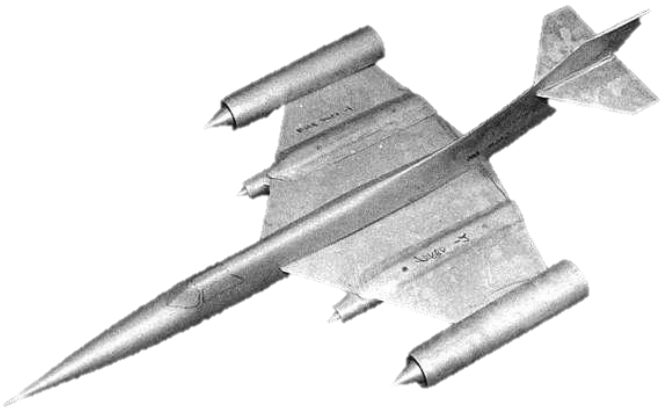
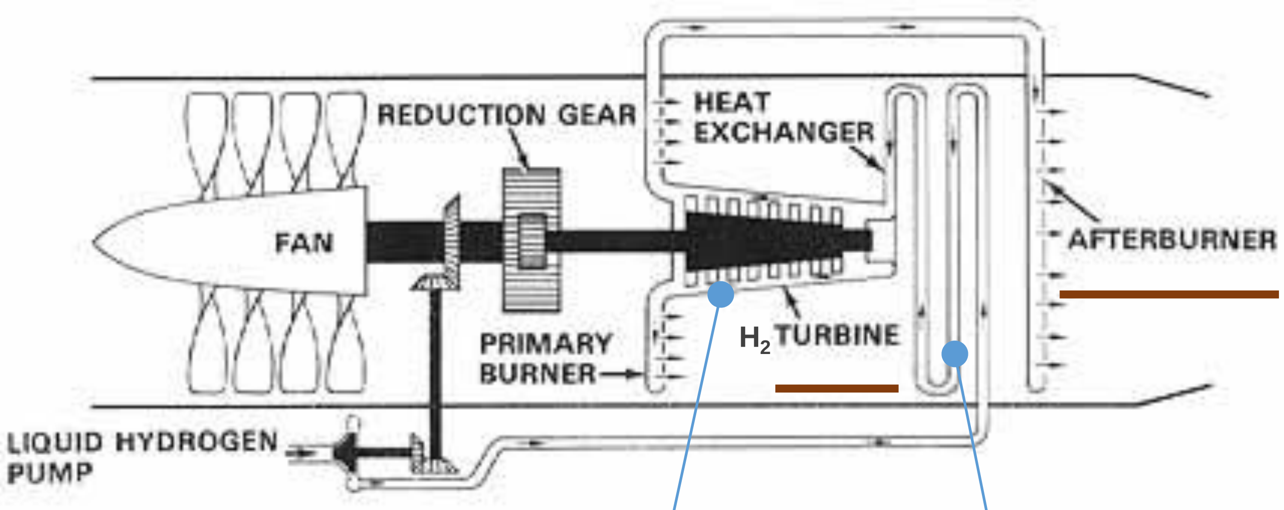
H_2 ENGINE EXPERIENCE / LESSONS: P&W 304 ENGINE → *USE THE COLD*

- 1950'S PROJECT SUNTAN . . . MACH-2.5 AFTERBURNING ENGINE
- LEARNING PAVES WAY FOR P&W DEVELOPMENT OF RL10 ROCKET ENGINE

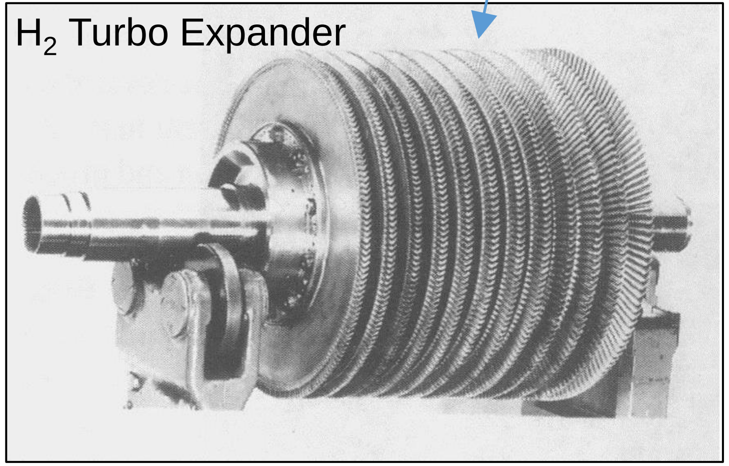


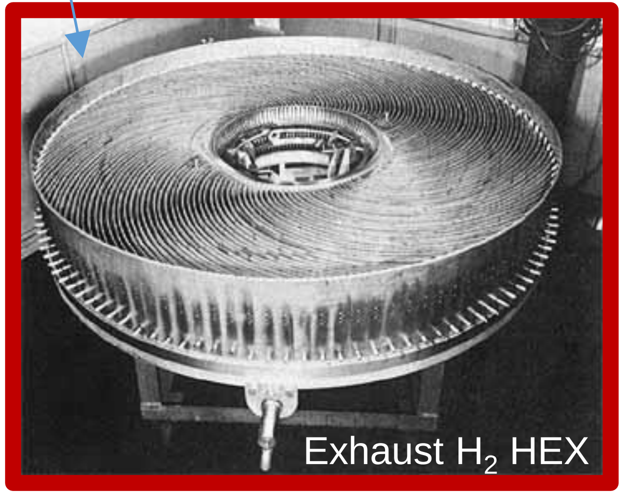


Power is generated by expanding LH2 after HEX

Augmentor provides thrust


Built & Tested P&W 304 Engine


H_2 Turbo Expander


Exhaust H_2 HEX

Take-Away: LH_2 HEX+engine built & run → could learning inform future engines?

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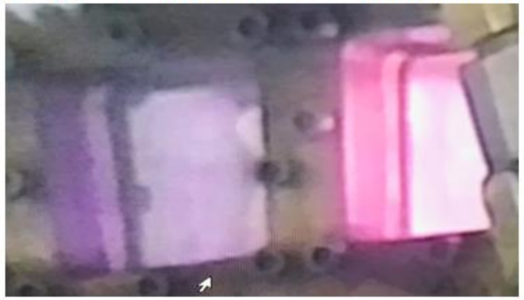
Hydrogen-Enabled performance → Water as Working Fluid

- **For *aircraft* propulsion:**
  - condense water from high-moisture exhaust (H_2 combustion)
  - inject water/steam into cycle
    - high-efficiency "combined-cycle"
    - low-NOx, stable H_2 combustion
- **For *power-generation*:**
  - condense or use other water source
  - inject steam into combustor & turbine
    - low-NOx H_2 combustion (high dilution)
    - and cycle efficiency benefit *(e.g. H_2-fired Cheng cycle)*
- **Applicable to aero-derivative engines & comb.** incl. transportation (shipping), and to industrial or frame GTs

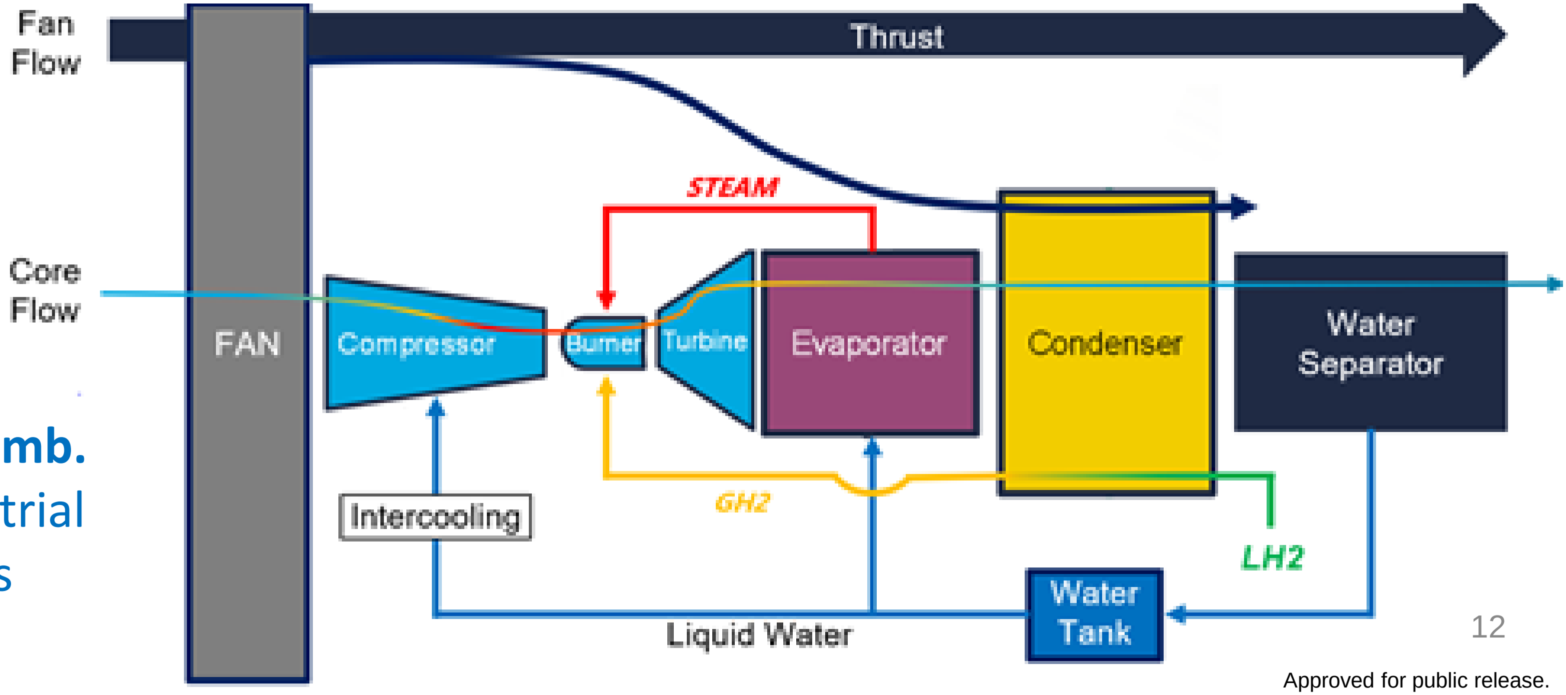
Hydrogen **S**team **I**njected **I**ntercooled **T**urbine **E**ngine

HySIITE

Hydrogen combustion in steam-air mix



Stable combustion to 0.8 steam-air ratio
Measured 99.3% NO_x reduction



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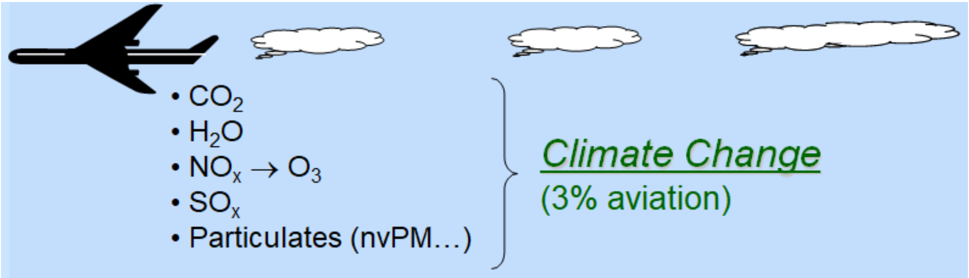
Emissions in Aviation – Water (vapor), nvPM, NOx & SOx

Performance Metrics, for Low-Carbon Fuel Options		Units *w/LHV fuel energy (Lower Heat. Val.)*	LH2 Liquid Hydrogen	NH3 Anhydrous Ammonia	Liquid CH4 / "eLNG" *e.g. SpaceX, Blue Origin*	SAF or Jet-A *(state of art)*
Environmental Impact (emissions)	CO_2 emissions from engine	kg / GJ	ZERO	ZERO	55 (↓ 24% vs. Jet-A)	72
	H_2O emissions	kg / GJ	*75*	*85*	*45*	*30*
	NOx	g / kg_fuel	target same as SAF	target same as SAF	< SAF	(1 –)10 – 30
	SOx	g / kg_fuel	ZERO	ZERO	ZERO	~ 1.0
	nvPM	g / kg_fuel	ZERO	ZERO	<< SAF	~ 0.1



Contrails: Studies underway
Carbon-Free fuels produce no nvPM (nucleation sites)
But they emit more water – impact uncertain…

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Gas Turbines in Prop. & Power → Carbon-Free Fuel Opportunities

3 Key Take-Aways:

- **Aviation difficult to de-carbonize, but new fuels offer efficiency improvements to help enable**
- **NH_3: Ammonia viable as a high-efficiency transportation fuel – incl. in aviation**
  - **technology spinoffs to power-gen, esp. when NH_3 stored as refrig. liquid**
    (for use as *working fluid*)
- **H_2: Hydrogen has challenges, but brings opportunity as cryo-fuel / cryo-fluid in aviation**
  - **cycle & combustion learning also applicable to power-gen, as LH2 or GH2**
    (e.g. *low-NOx* H_2-fueled aeroderivative cycles)

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BACKUP

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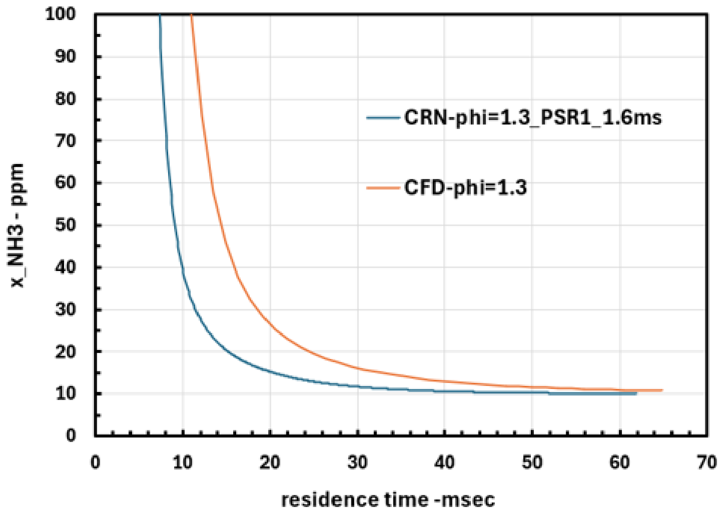

Figure 5.3 x_NH3 vs residence time, T3=850F, T_fuel=310.9K, Swirler ϕ=1.3

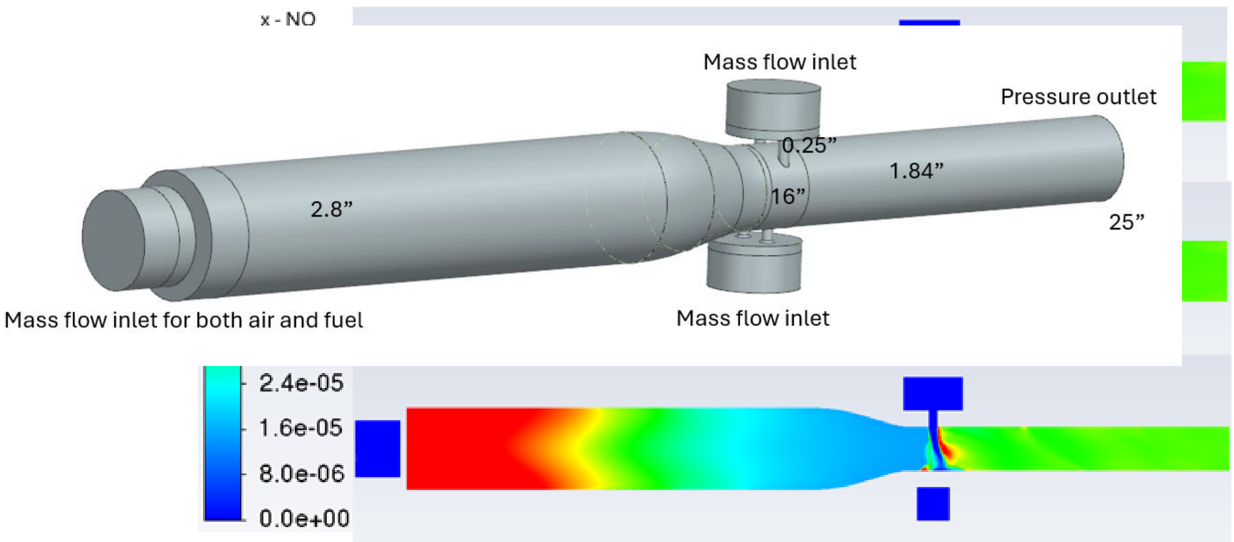

Figure 5.8 x_No, T3=850F, T_fuel=310.9K, Swirler ϕ=1.3

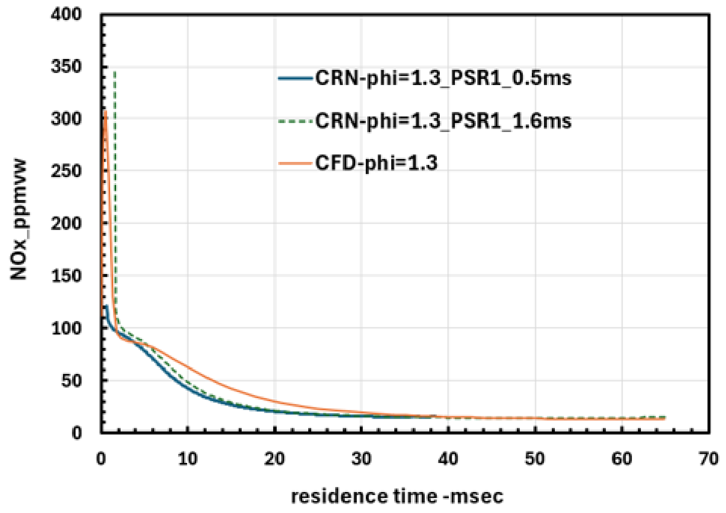

Figure 5.4 NOx vs residence time, T3=850F, T_fuel=310.9K, Swirler ϕ=1.3

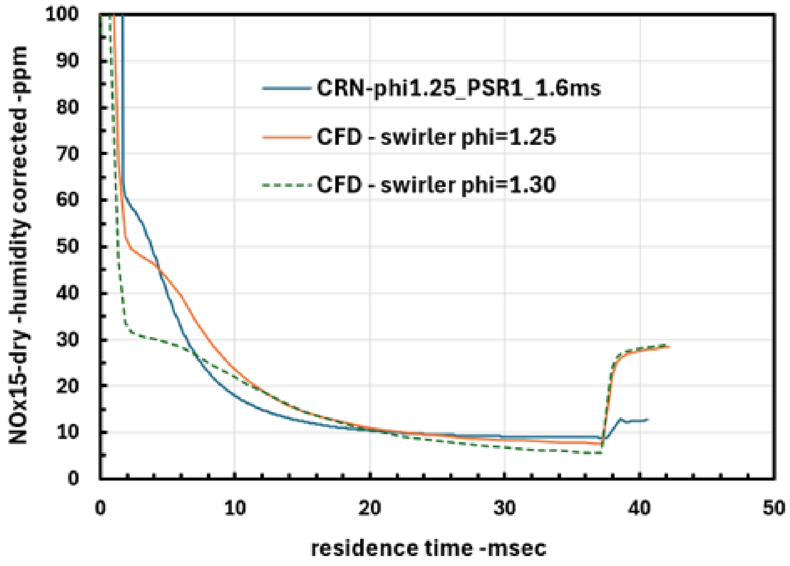

Figure 5.9 NOx15_dry_humidity corrected vs residence time, T3=850F, T_fuel=310.9K, Swirler ϕ=1.3

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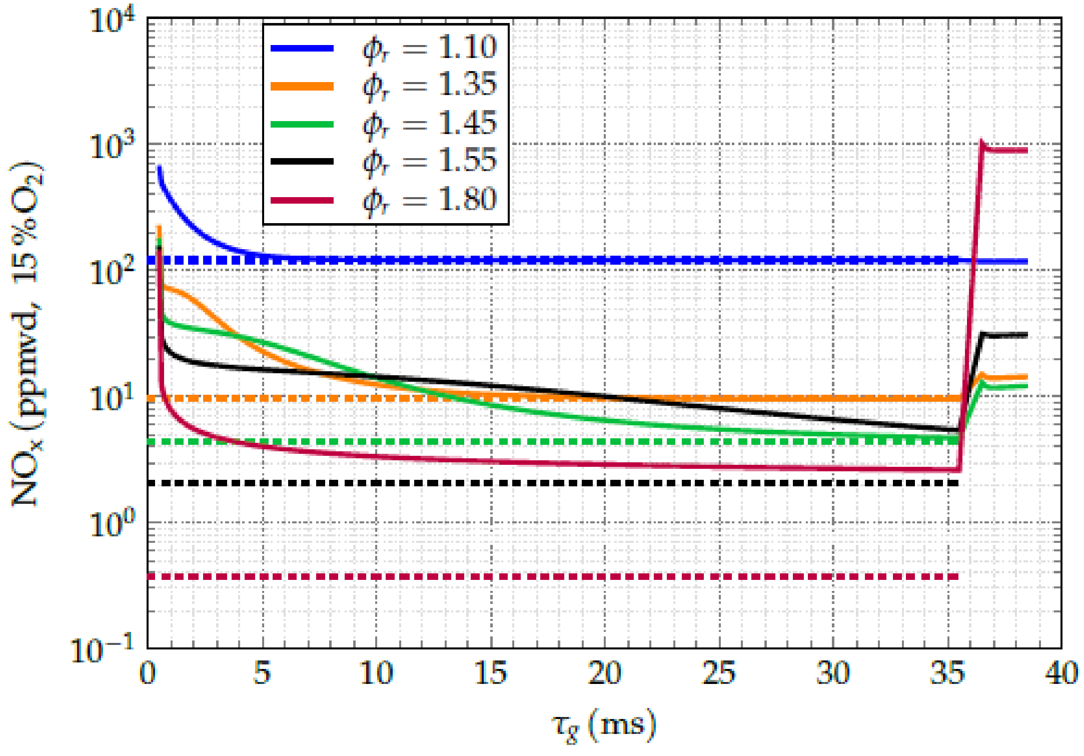
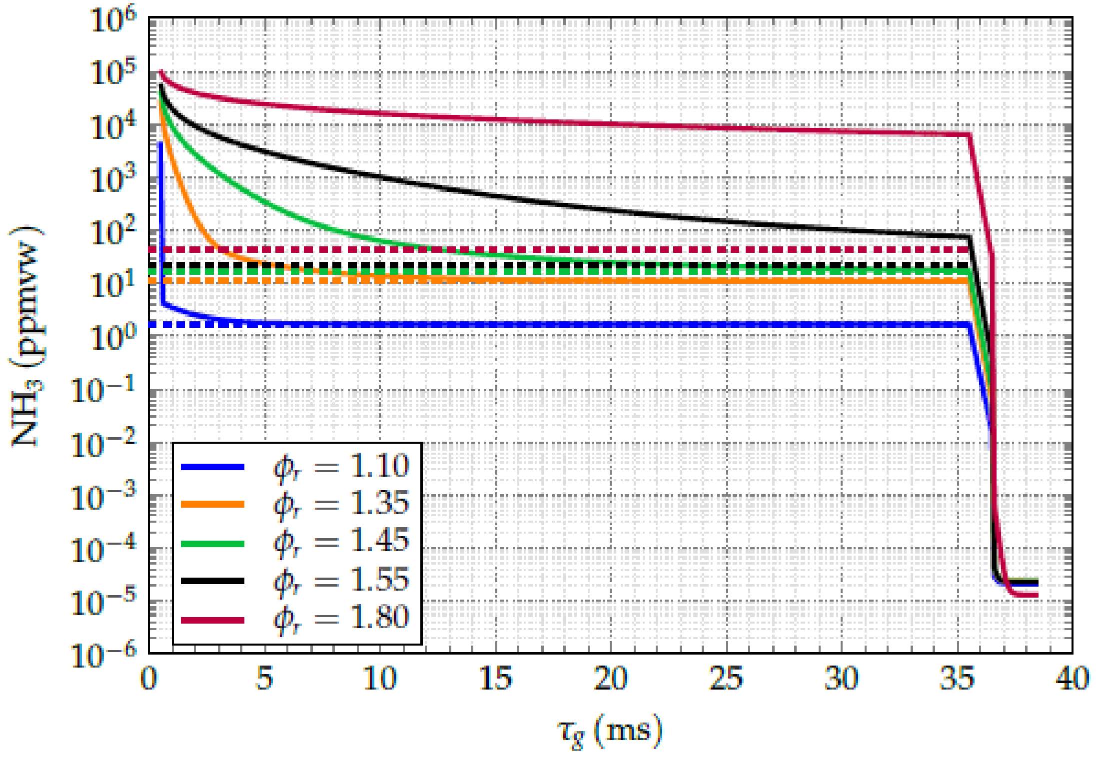
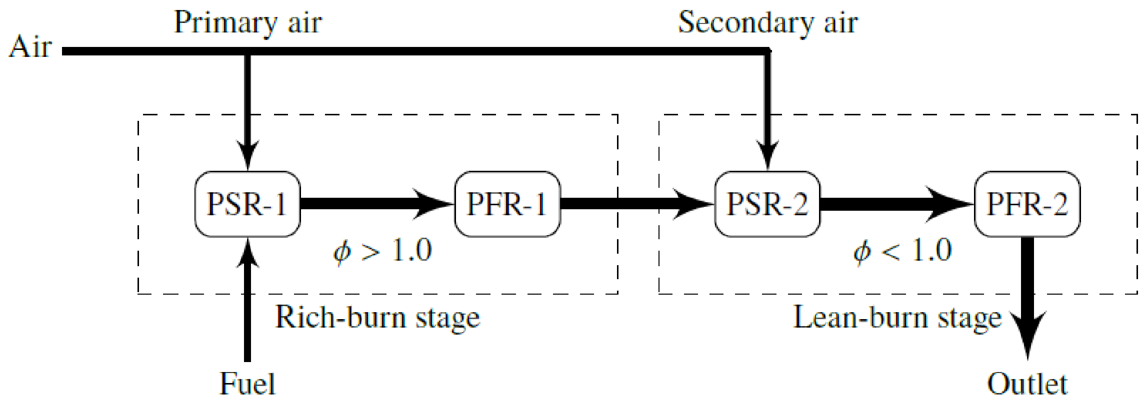


(a) Evolution of NOx with global residence time



(b) Evolution of NH_3 with global residence time



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Re-visit NH_3 for turbine propulsion …Physical properties…

Fuel Property	Jet-A (ambient liquid)	H_2 (–253 °C liquid)	NH_3 - anhydrous (–33 °C liquid)
Specific Energy (MJ/kg)	43 MJ/kg	120 MJ/kg	18.6 MJ/kg
Energy Density (MJ/L)	34 MJ/L	8.5 MJ/L	12.7 MJ/L
T_saturation @ 1-atm (°C)	175 - 250 °C	–253 °C	–33 °C
T_saturation @ 10-atm (°C)	325 - 350 °C	–242 °C	+25 °C
Conductivity, k (W/m-K)	0.1 W/m-K	0.1 W/m-K	0.6 W/m-K
Heat Capacity, Cp (kJ/kg-K)	2.0 kJ/kg-K	9.7 kJ/kg-K	4.5 kJ/kg-K
Heat of Vaporization, h_fg (kJ/kg)	350 kJ/kg	446 kJ/kg	1370 kJ/kg
Heat of Cracking reaction (kJ/kg)	coking issues	N/A	2700 kJ/kg
"Gamma" ratio, Cp/Cv (in gas state)	< 1.05 (C8+)	1.4	1.3

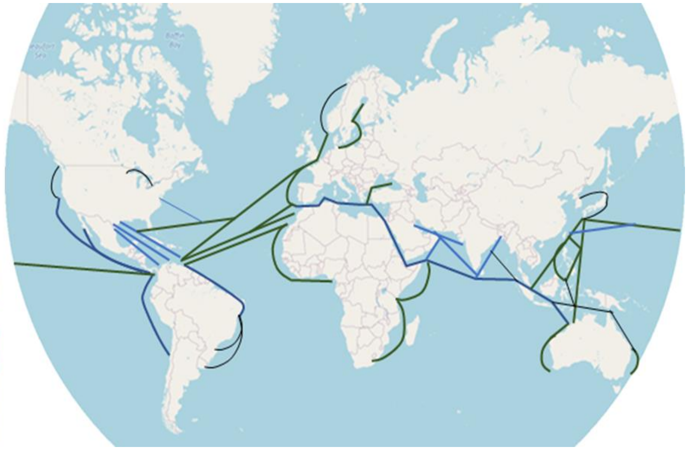
Ammonia properties are "familiar" & useful

Energy density ~ Methanol (~1/2 of Jet fuel)

Storage conditions ~ Propane

Ammonia is a well-known refrigerant, with excellent k, Cp, h_fg

Unique capabilities as a fuel, with potential for efficiency gains …



- Global Jet fuel use ~200B kg/yr.
- Global NH_3 production ~175B kg/yr.
- Global NH_3 infrastructure @ scale

2nd most transported chemical in world

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Sustainable Aviation Technology Development …

Propulsive Efficiency ↑ w/ Electrification

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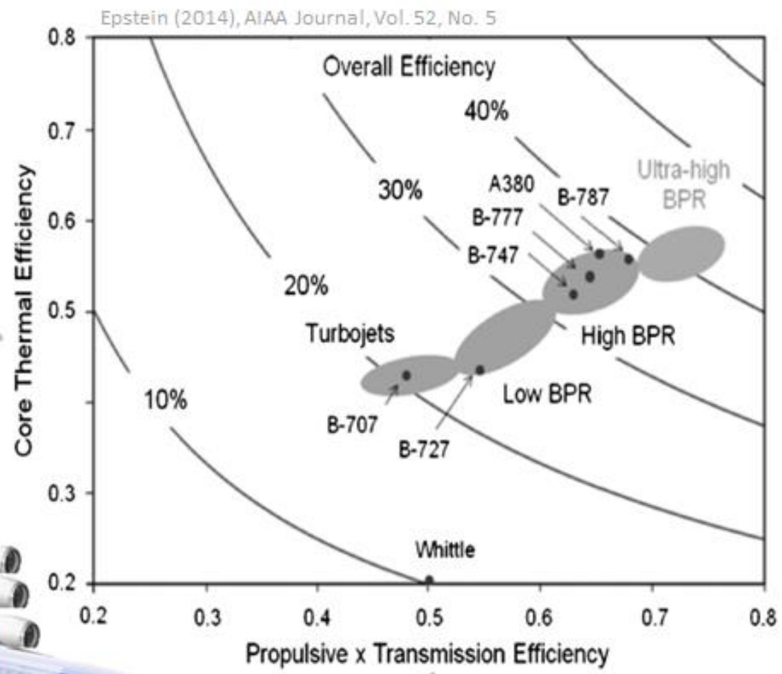
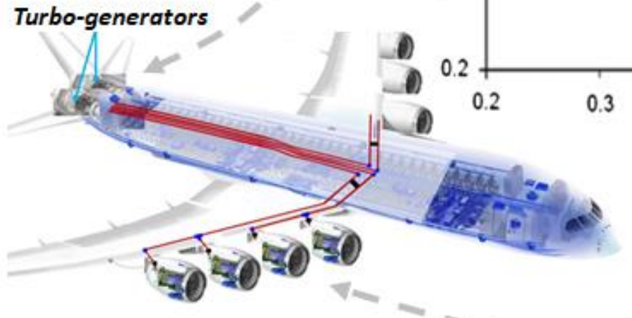
ZAPturbo
CO-Power

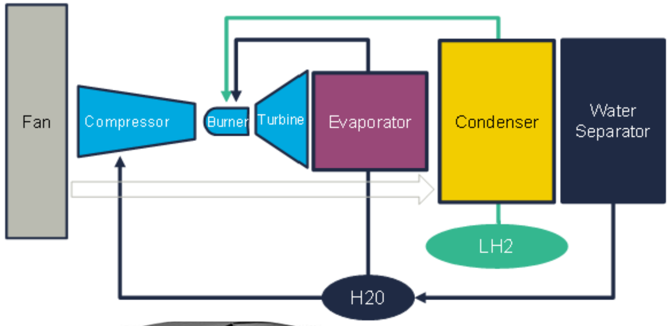


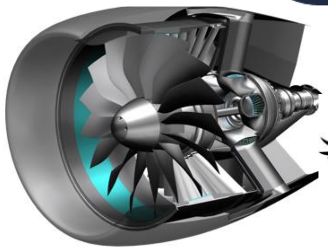


RTX
SOARING
ULTRA-Compact

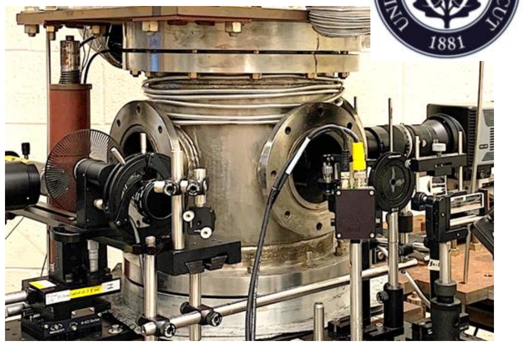
- **Further reduce fuel weight & volume**

Alternative Fuels for Reduced Carbon

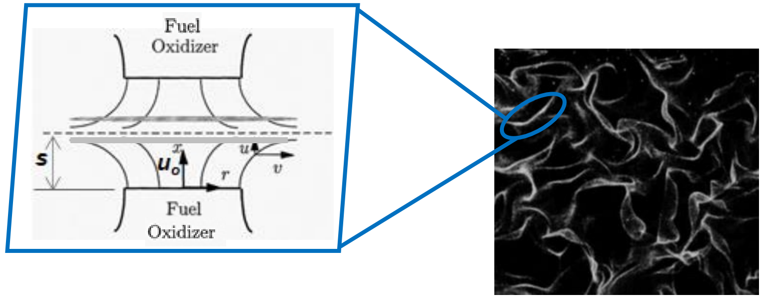




ARPA-E HySIITE for H_2 propulsion



NH_3 flames



- **DOE-NETL "LOAD-Z" project to develop & test NH_3 combustion technology for gas turbines**

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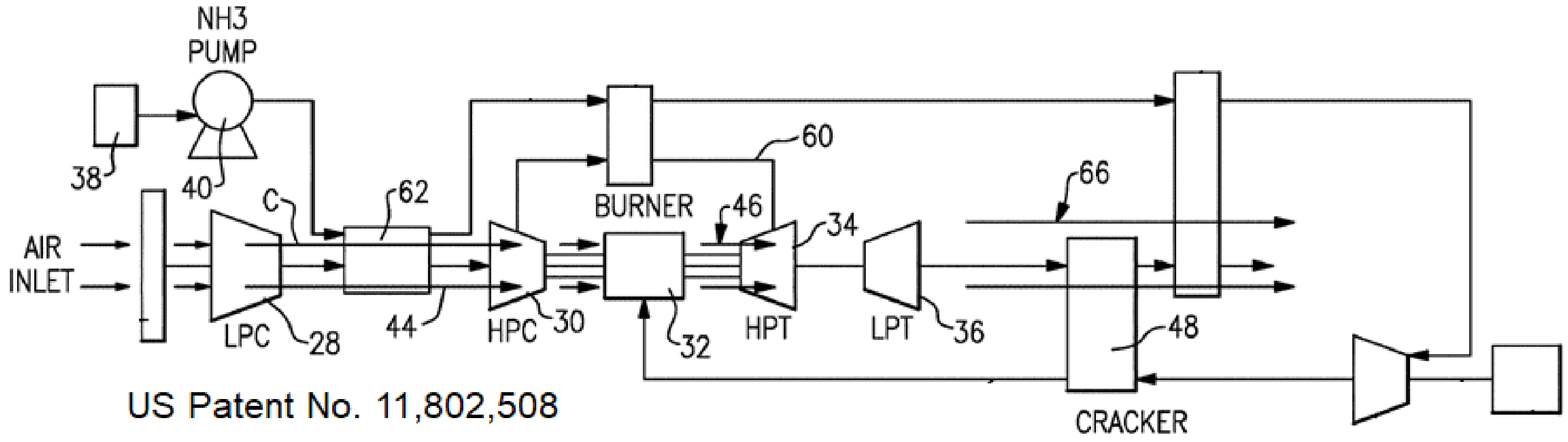
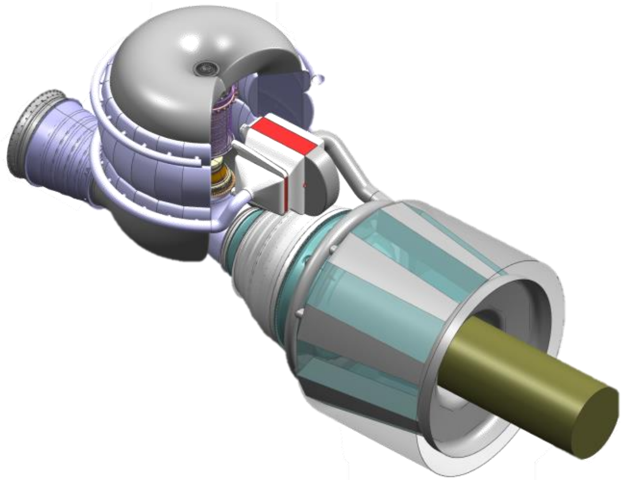
NH_3 Propulsion: Learned from System Studies ("where we landed")

- **"Chemical recuperation" maximized by cracking <u>downstream</u> of NH_3 turboexpander**
  - T_{HEAT_SOURCE} from efficient GT-cycles insufficient for high %-cracking @ high-P_{NH3} … (+ catalyst sintering @ high-T)
  - Maximize CC-efficiency with $Q_{CRACKING}$↑ (%-cracking ↑) despite $W_{TURBOEXPANDER}$↓
- **NH_3 effective for chilling cooling-air to turbine**
  - Significant cooling obtained w/ compact low-ΔP HEX
  - Enables high-TRIT (T4) for efficiency & high $T_{EXHAUST}$ to drive cracking *(90% NH_3 → H_2)*
- **NH_3 intercooling enables high-OPR cycle**
  - Provides intercooling without heat rejection (without energy loss) for efficiency ↑
  - NH_3 has ample cooling capacity at engine fuel-flow rates
  - NH_3 is effective liquid "refrigerant" for compact intercooling HEX

Unique to NH_3!



US Patent No. 11,802,508



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Challenge: High-Pressure NH_3 Cracking (fight equilibrium)

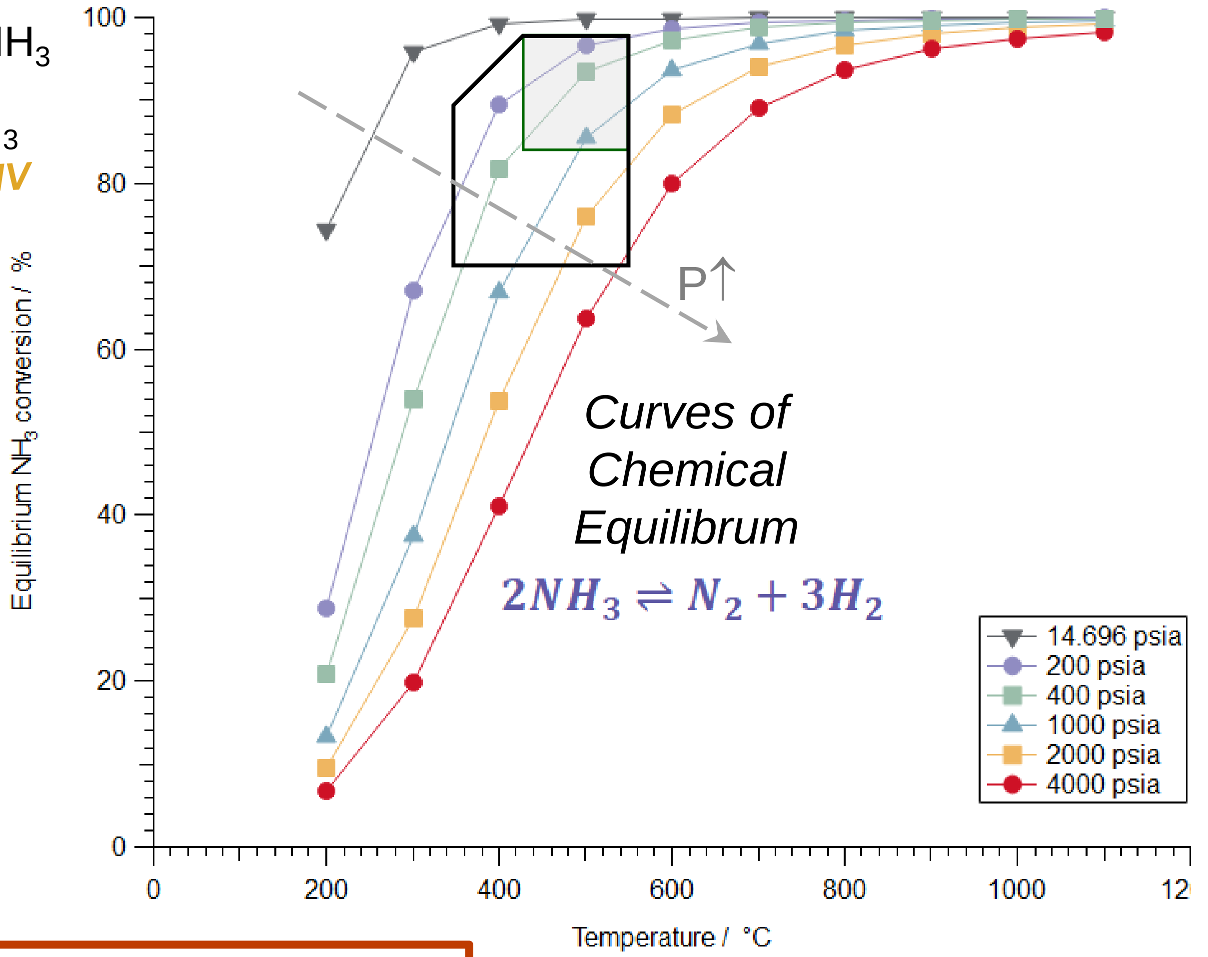
Cracking: $NH_3 \rightarrow \frac{3}{2}H_2 + \frac{1}{2}N_2$ … $\Delta H_{\underline{ENDO}\text{-thermic}}$ = + 2.7 MJ/kg-NH_3

Synthesis: $N_2 + 3H_2 \rightarrow 2NH_3$ … $\Delta H_{\underline{EXO}\text{-thermic}}$ = – 2.7 MJ/kg-NH_3

15% of LHV

Constraints: (design intent)

1. Avoid gas compression work (loss)
   - *__pump liquid__ NH_3 before crack to H_2*
2. GT = internal combustion engine
   - $P_{FUEL} > \mathbf{P_{COMBUSTOR}}$
3. Desire high %$_{CRACKING}$ $NH_3 \rightarrow H_2$
4. Use only waste-heat for cracking
   - $T_{CRACKING} < \mathbf{T_{EXHAUST}}$



2 Objectives:

1. Seek optimal tradeoff: Cracking -vs.- Expansion Work
2. Demonstrate catalyst activity & durability at high-P

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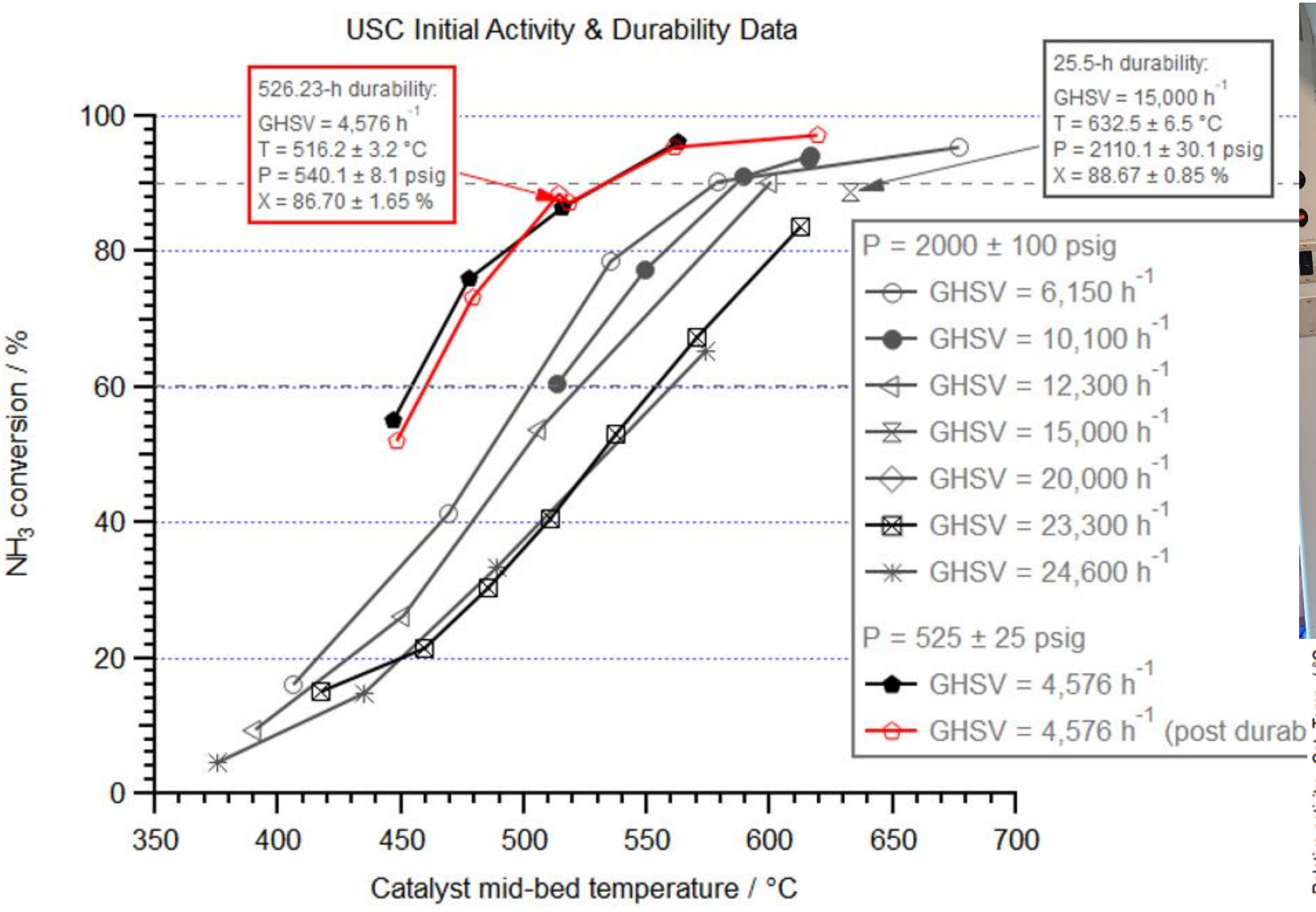
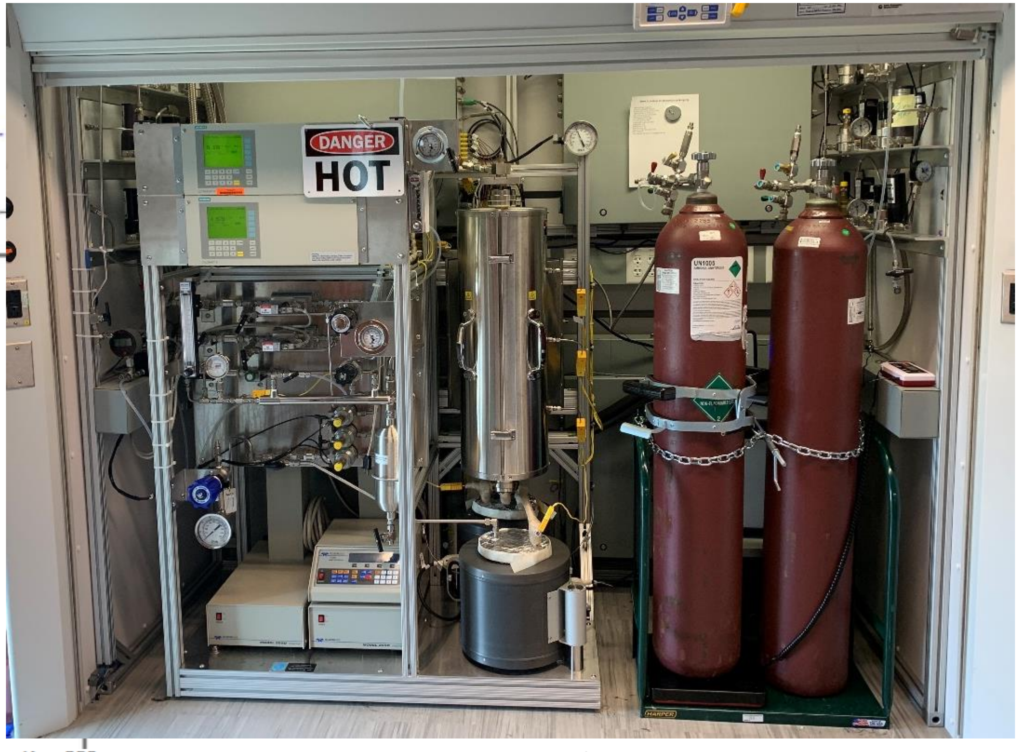
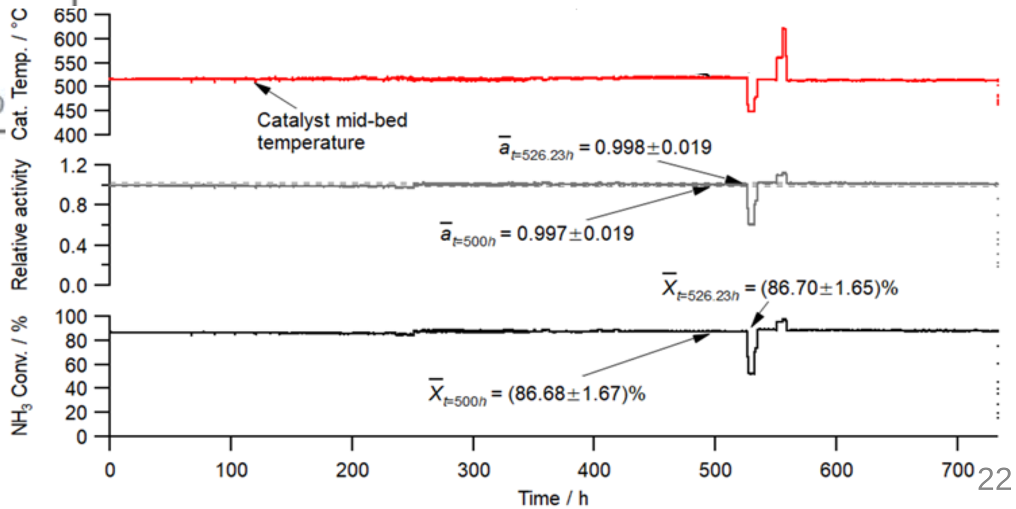
NH_3 Cracking Catalyst: High-P Testing for Activity & Durability







- Catalytic cracking demonstrated at >2000 psia
- Catalyst durability demonstrated for >700 hours

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END

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