Ammonia for Aviation: Benefits, Challenges, and Opportunities

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Application Description: Aviation

- Primary modality is combustion engines
- Legacy fuels are:
  - Unleaded kerosene (Jet A/A1)
  - Naphtha-kerosene (Jet B)
  - Avgas (Aviation gasoline)
- Kerosene primarily used in gas turbine engines and diesel, avgas for small airplanes
- Gas turbine consumption for commercial aviation is a large % of the market
- Climate forcing emissions:
  - Net positive CO_2
  - NO_x
  - UHCs, soot, SO_x, CO
  - Contrail formation

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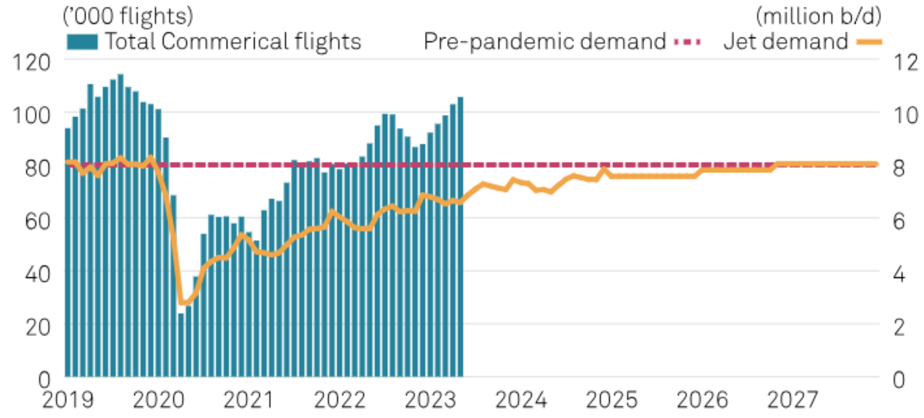
Jet Fuel Market At a Glance

Recent Trends and Market Today

- 2019, aviation accounted for about 8-9% of global crude oil use
- 2-3% of total energy use and CO2 emissions
- In terms of volume delivered to the plane:
  - 2019: 95 billion gallons or 290 Mt of Jet-A
- Industry hit hard by COVID 19
- Recovering to trend at about 6-7% global crude consumption



Note: Jet demand for 2025-2027 shown as annual averages
Source: S&P Global Commodity Insights

Substantial predicted growth:

- Growth projections from Boeing CMO
- Doubled fleet size
- Tripled RPKs from 2022 (traffic demand)
- More than double cargo demand

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The Case for Ammonia In Aviation

Compare with other low carbon solutions: SAF, Hydrogen, Electric/batteries

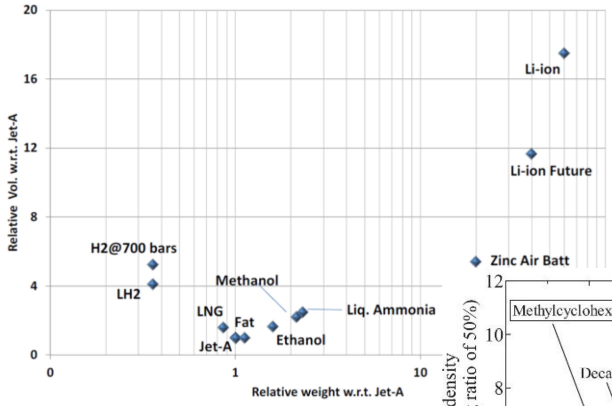
- Lower specific energy than jet fuel and hydrogen, but not nearly as bad as batteries (5170-5910 W-hr/kg)
- Best volumetric H2 density out of all hydrogen carriers
- Non-cryo storage -- can be stored inside of a wing fuel tank at -33C
- Existing infrastructure, transport mechanism, market
- Potential for lower net delta cost per CO_{2eq} abated than other fuels

Near term market potential:

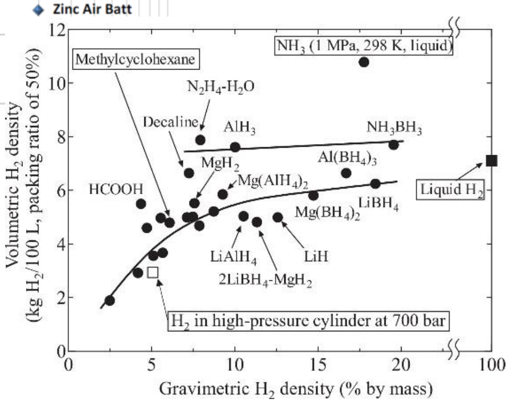
- Can be cracked into a mixture of gaseous ammonia and hydrogen that (supposedly) has very similar burn properties to jet fuel
- Can potentially be retrofit to existing engines / airplanes (doesn't necessarily require a new design)

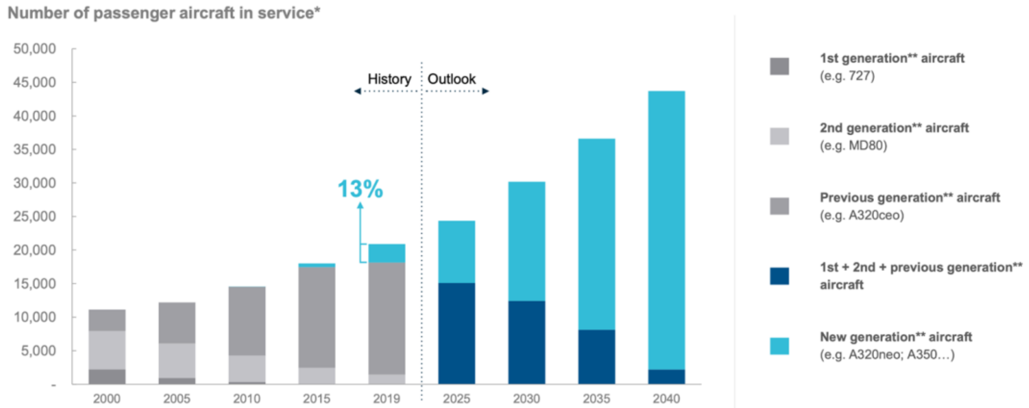
Unique Efficiency benefits:

- High specific heat / capacity
- No coking
- Cracking → Hot fuel improves efficiency
- Synergies with other ideas, such as recuperation or bottoming cycles to improve engine thermodynamic efficiency



Gangoli Rao (2020)





Airbus Company. Airbus Global Market Forecast 2021-2040. 2021.

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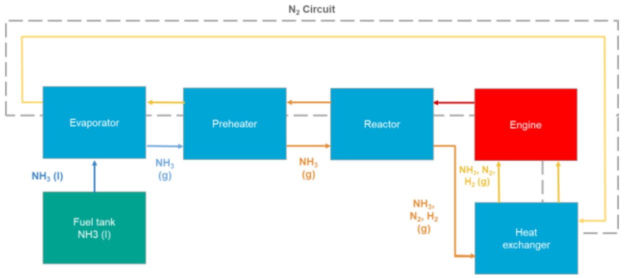
State of the Art: University Research

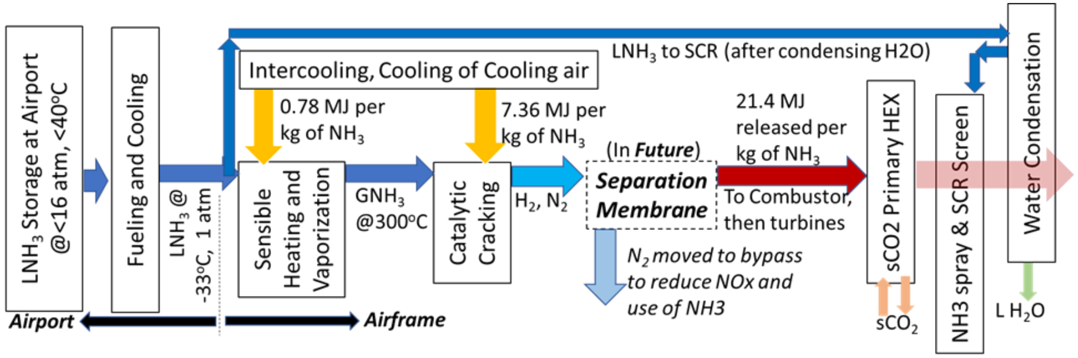
TU Delft – A320-NH3

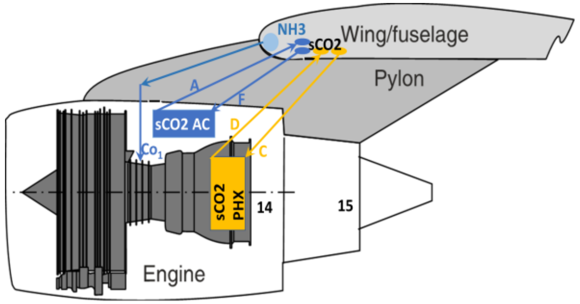
- Retro-fit of A320neo
- Single aisle application
- Worked fuel storage on aircraft, airport and safety requirements
- Cracking system implementation
- Inter-turbine burner



ALFA (Funded by NASA: University of Central Florida)

- B737Max retro-fit
- Novel way of utilizing ammonia cooling power within an engine cycle (improved efficiency)
- Single aisle application
- Strive to reduce or eliminate NOx emissions
- Work fuel storage on aircraft, airport and safety requirements

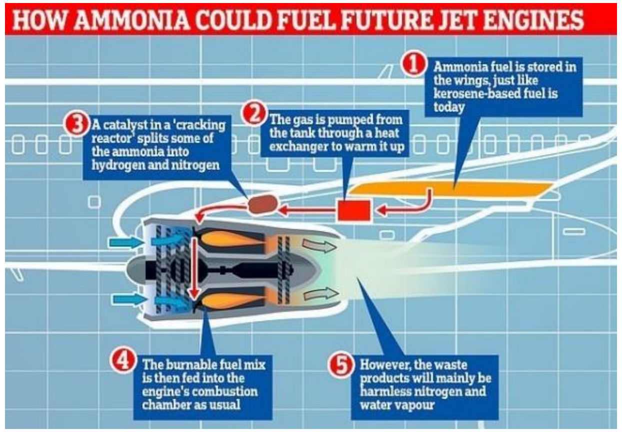




State of the Art: Industry Activities

Reaction Engines:

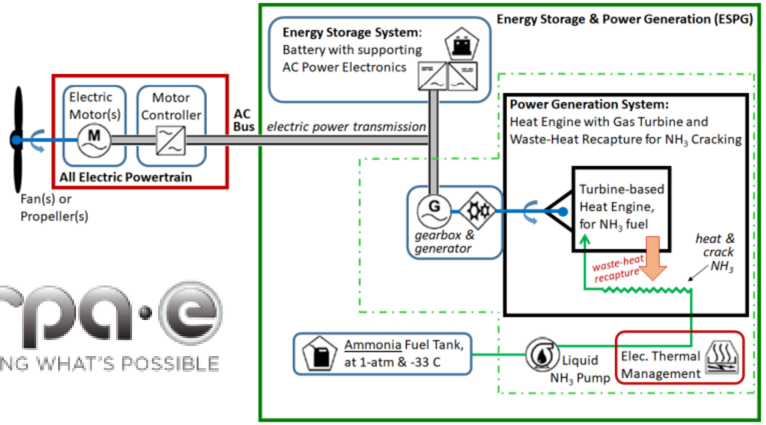
- The density of liquid ammonia allows for conventional aircraft configurations
- May be possible to retrofit into an existing engine, resulting in a zero-carbon jet
- Could start serving the short haul market well before the 2050 target currently set by the industry.



Reaction Engines: James Barth, quoted in Reaction Engines announcement, Reaction Engines, STFC engaged in ground-breaking study on ammonia fuel for a sustainable aviation propulsion system, August 18, 2020

Zero-carbon **A**mmonia-**P**owered **Turbo**electric Propulsion System (ZAPturbo)

- Provide a liquid-fueled, carbon-free, non-cryogenic aircraft propulsion system for future flight.
- Leverage the unique properties of ammonia to achieve ultra-high energy efficiency (66%), to offset the extra weight-per-energy of ammonia.



arpa·e CHANGING WHAT'S POSSIBLE

ARPA-E and RTRC: https://arpa-e.energy.gov/sites/default/files/2021-02/04_Smith_ZAPTurboKickoffJan2021_vIII.pdf

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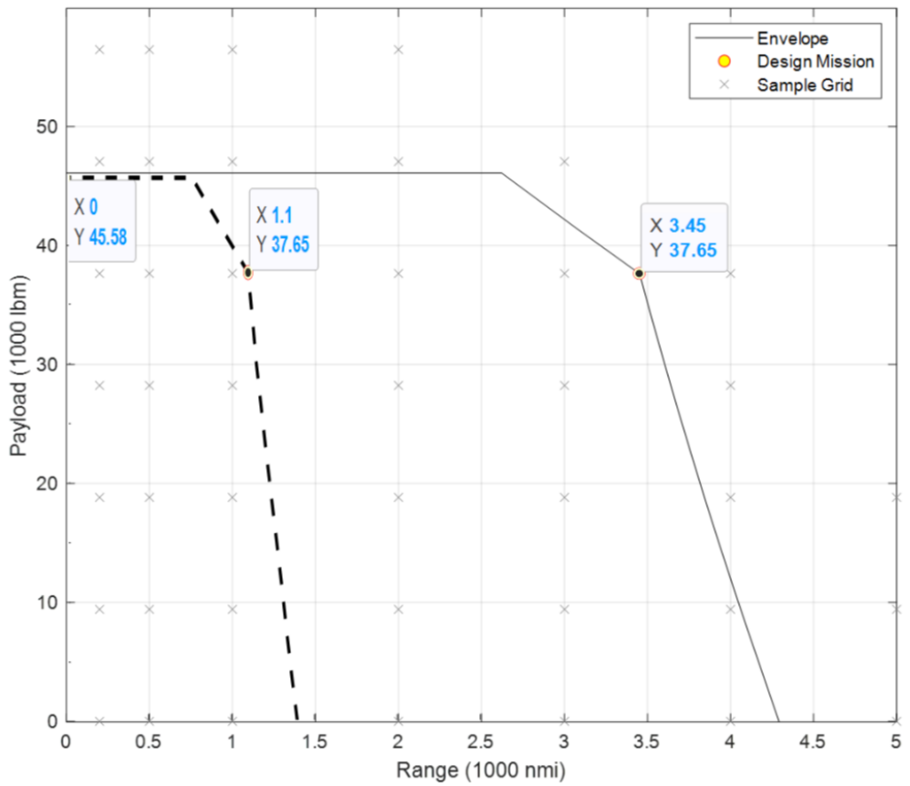
So What Have We Learned? Major Challenges?

1. Efficiency improvements in the engine are real
   - Engineering challenges but no real road blocks
2. Likely range limits due to either weight or volume (storage challenge) – potentially up to 1700 nmi (3000 km)
3. Safety and handling issues are a challenge – Relevant regulations?
4. Stability of combustion – On-going Research
5. Cracking performance vs. cracking weight / integration
6. NOx emissions – Probably solvable

Ammonia powered vs. JET-A powered baseline model



Bold dashed line – Ammonia powered B737-8 envelope
Undashed line – Baseline B737-8 envelope

Market Opportunity

- Single aisle market opportunity corresponds to a theoretical ***maximum*** of about 30% of current jet fuel due to range limitations
- This would correspond to converting ***all*** flights < 3000 km
- In reality it would be some fraction of this, as market capture would take time, and many vehicles may not be able to be retrofit
- For context, in 2019, aviation consumed about 95 billion gallons of jet fuel or about 288 Mt
- Ammonia energy equivalent: 660 Mt (Very large quantities in the context of current ammonia production)

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Thank you!