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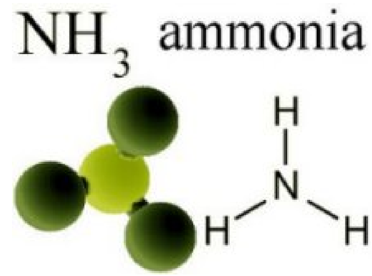

Ammonia Based Fuels For Environmentally Friendly Power Generation

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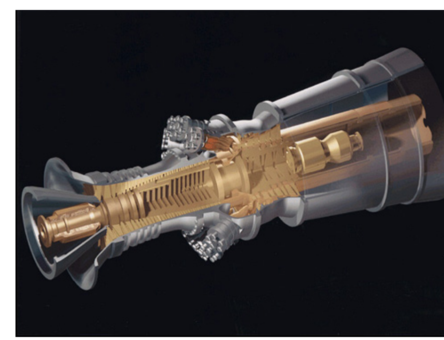

September 24, 2013

Why Electricity Generation?

Transportation vs Electricity Generation

Due to its high hydrogen density, ammonia has been studied as transportation system fuel extensively

"DOE does not plan to fund R&D to improve ammonia fuel processing technologies for on-board use on **light weight vehicles** at the present time"
Ref: *Potential Roles of Ammonia in Hydrogen Economy*, *DOE Report, Feb 2006*.

The following are quoted as the main reasons
- Safety – toxicity
- Ammonia cracking issues: start up, efficiency, conversion rate
- Storage: Lack of light, compact and robust storage tanks

	Transportation	**Electricity Generation**
Safety	Very critical	Not as critical
Cracking	Cracking reactors heavy/expensive	Easily done
Storage tank weight	Critical	Not an issue
Storage tank robustness	Need to be "Indestructible"	Existing storage tanks are suitable
Distribution	Complicated	Relatively simple
Start up	Problematic	Not many start ups
Operational	Pumps operated by unprofessionals	Delivered/handled by trained pers.

Major shortcomings of ammonia for transportation systems are NOT relevant to electricity generation

Why Gas Turbines?

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Gas Turbine Power Generation

Older plants are rapidly being displaced by gas turbine power generators

- Gas turbines supplied 15% of US power generation in 1998.
- Portion will be 39% by 2020.
- Of new demand 81% is for gas turbine power.
- Market is ~ $10 billion. About 700 to 800 new units sold per year.

Engine Types in Use

- Heavy duty gas turbines - centralized power production, 30 to 500 MW.
- Lightweight gas turbines - derived from aircraft engines, generally less than 60 MW.
- Micro gas turbines - distributed power, less than 5 MW

Why Gas Turbines?

- High efficiency - Up to 60% with steam co-generation.
- Low emissions - NOx < 10 ppm.
- Low installed cost - 25,000 hr maintenance interval.
- Multi-fuel capability - Natural gas (methane) is fuel of choice when available. Fuel transition while running

One of the Applications

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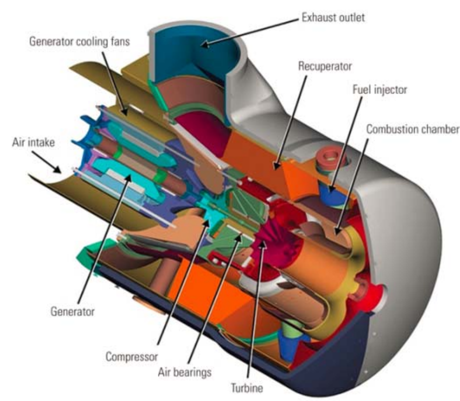
Applications – Small Scale

NH3 Production

- Small scale NH3 production units based on electrolysis are currently available
- These can be converted to mobile systems
- If SSAS technology is developed successfully, efficient, cost effective and compact units can be manufactured
- NH3 can also be produced from HC feed stocks



NH3 Fuel

- NH3 can be easily and safely stored
- Gas turbines can be used to generate electricity
  - Microturbines: 30 kW-200 kW
  - Aerobased: 10 MW
- Exhaust gas can be used for heating
- Eventually NH3 can be used in mobile applications

Background
Ammonia Fired Turbines

Gas Turbine Power Generation – Fuels Comparison

Fuel	Fuel/air ratio*	Tcombuster* K at 20atm	Texhaust K at 1 atm	Enthalpy change (work) kJ/kg
Methane	0.058	2277	1260	1551
JP-4	0.068	2342	1313	1539
Ethanol	0.111	2295	1289	1546
NH3	0.164	2092	1114	1549

* Stoichiometric fuel/air combustion at a pressure ratio of 20:1

- NH3 requires higher fuel mass flow rate
- NH3 generates the same work output at lower temperature
- Or NH3 generates more power at the same temperature

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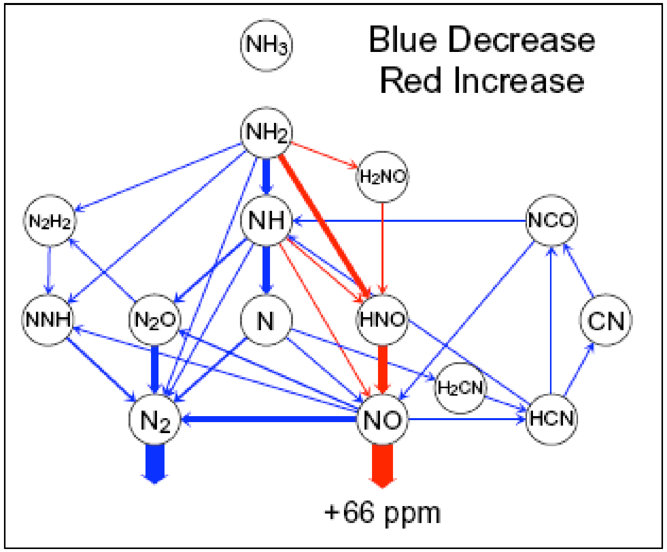
Past Experience with Ammonia Fueled Gas Turbines

History

- Ammonia as a turbojet engine fuel has been tested in 1960's
- At least two DoD programs (reports available)
- Some recent research activity in University of Florida
- No active programs as far as we know

Lessons Learned

- Ammonia is a satisfactory substitute for hydrocarbon fuels in a gas turbine engine
- Complexity and cost of engines using ammonia vapor combustors will NOT be significantly greater than existing hydrocarbon engines
- Use of ammonia would also lead to reduction of NOx emissions ?



Oxidization chemistry of ammonia is well established

Technical Challenges

- Low flame temperatures and slow kinetics results in challenges with pure ammonia in a turbojet combustor
- Stable efficient combustion with liquid NH3 is problematic. Additives would help with this issue
- The DoD programs concluded that ammonia in the vapor phase can be burned in a turbojet combustor. This requires a heat exchanger to vaporize the ammonia
- Cracking helps flame stability

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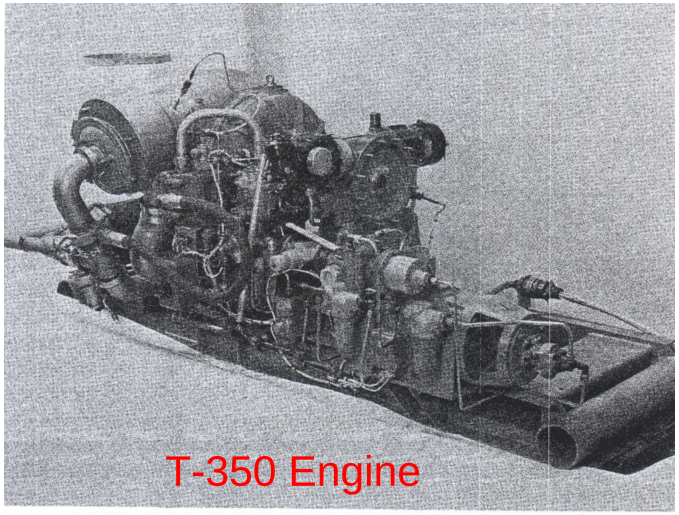
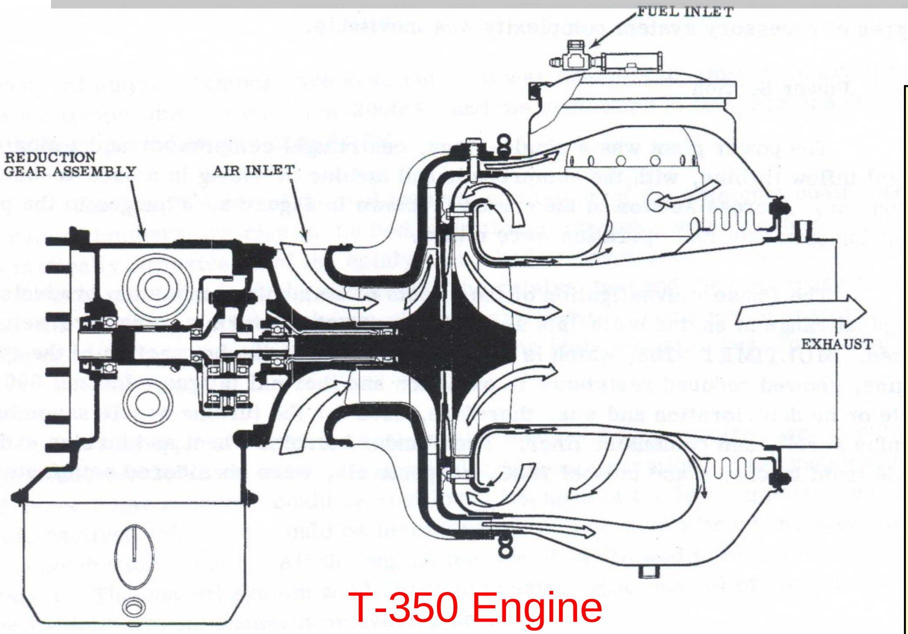
Past Experience with Ammonia Fueled Gas Turbines

- Investigations have been conducted by Solar Company and UC Berkeley in the 60's
- Solar used its 250 HP model T-350 single can burner engine.
- UC Berkeley studies were limited to subscale combustors
- Performance of the T-350 engine with ammonia is compared to the performance with JP-4
- Tests were limited to ammonia in vapor phase



T-350 Engine



T-350 Engine

Some Observations

- Both vapor and catalyst combustors have been tested.
- Using ammonia at 2.35 times the HC fuels resulted in cooler turbine inlet temperatures at a given power.
- When the turbine inlet temperatures are matched, the ammonia engine resulted in a power increase of 10-20%.
- Efficiencies were high with the ammonia combustors.

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Development Path

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SPG/MADA's Core Competence

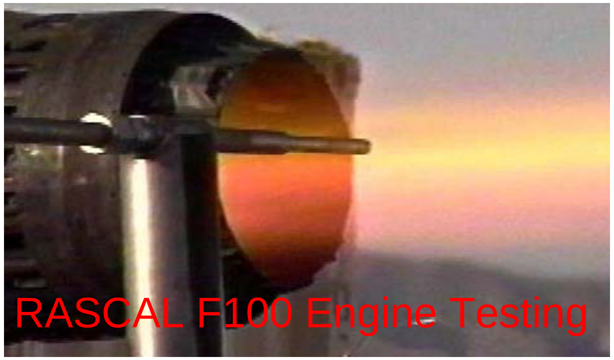
SPG/MADA personnel have broad experience in

- Combustion, thermochemistry of fuels, design and analysis of gas turbines
- Testing of gas turbine engines and rocket motor systems
- SPG is an experienced DoD contractor (DCAA approved accounting system etc…)


Hybrid Motor Development Testing


RASCAL Facility, Mojave CA

We have access to several J79 and J85 engines and all test equipment from the RASCAL program


RASCAL F100 Engine Testing

SPG/MADA's capabilities include

- Laboratory testing of fuel properties
- Testing of turbojet engines (AEROTEC test facility in Butte Montana)

Development - Program Elements

Phase I – Feasibility (Funded by SPG IR&D Funds and Montana Board of Research and Commercialization Technology)

- Objective: Evaluate the feasibility and economical/technical viability of the concept
- Conduct feasibility studies: Modeling of ammonia combustion, testing in combustors and design of fuel nozzle for microturbines and J79 engine

Phase II – Technology Development

- Objective: Develop the necessary technologies to implement the concept
- Work includes: Fuel formulation and laboratory testing, engine cycle analysis, extensive engine testing (using engines C200 and J79 – two exist in the AEROTEC facility), development of fuel conditioning systems, coordinate with NH3 plant manufacturers

Phase III – Pilot Plant

- Objective: Implement the concept on a small gas turbine power generation plant
- Work includes: Conversion of the existing facility to an ammonia fired gas turbine, evaluation of the economical viability of the concept
- Partner with DoD

Phase IV – Implementation

- Objective: Convert existing gas turbine power generation facilities to burn ammonia and develop new ammonia-fired gas turbines if necessary
- Partner with a gas turbine producer

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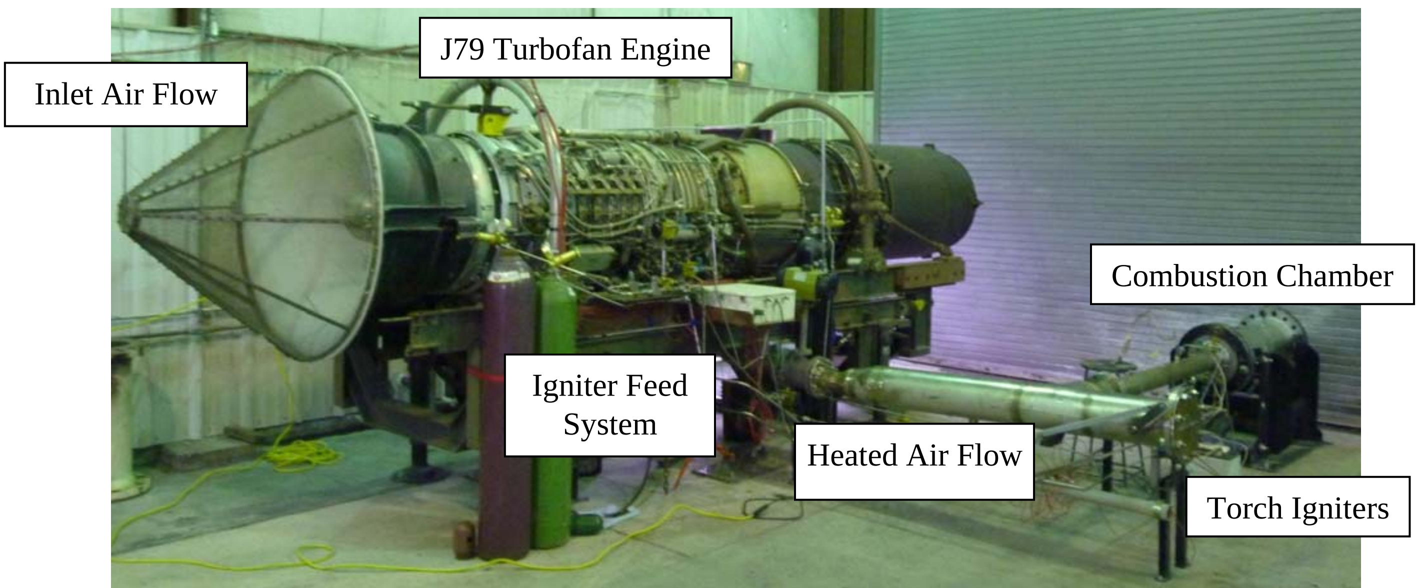
Phase I Progress – Developed of Test Set up

- Test rig designed to simulate gas turbine combustor conditions
- Bleed air from a J-79 turbofan engine supplies high pressure, hot air for combustion
  - Air flow rates of >8.0 kg/s can be achieved
- At full thrust, an NH_3 mass flow rate of 0.690 kg/s required for stoichiometric mixture
- NH_3 vapor is pulled from the run tank and mixed with N_2/H_2 to simulate cracking
- Extent of simulated cracking is precisely controlled



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Phase I Progress – NH3 Test Setup

- Primary Measurements
  - Flow rates
  - Pressures
  - Temperatures
  - NOx
- 3 kHz sampling rate

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Phase I Progress – Achievements

Achievements to Date

- Developed a facility to test ammonia combustors
- Achieved self sustained combustion with ammonia in a simulated gas turbine combustor
- Developed a combustor configuration suitable for burning ammonia
- Successfully simulated cracking
- Developed expertise in the safety of ammonia
- Developed operational experience with ammonia
- Designed a facility to burn ammonia using existing C200 microturbines
- Developed a technology to crack ammonia in a cost effective and efficient way

Cracking Technologies

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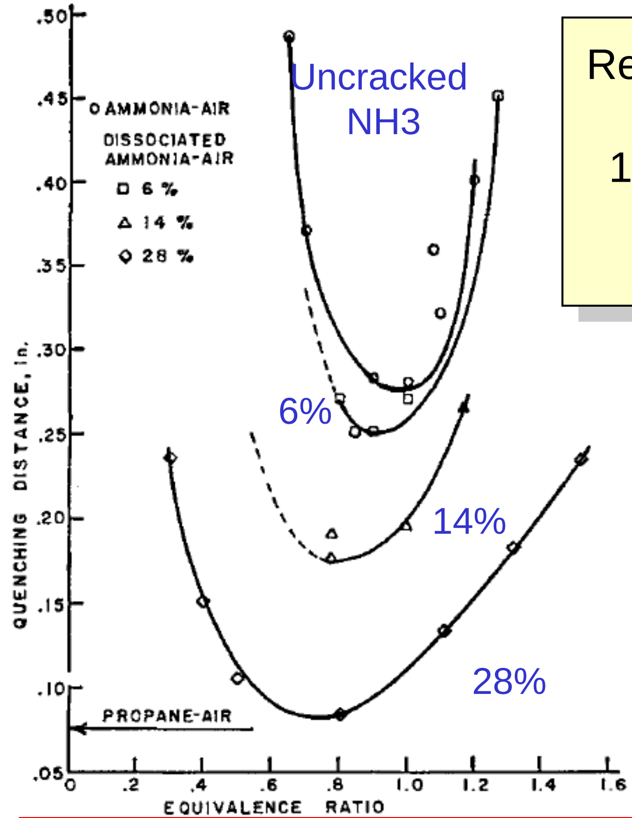
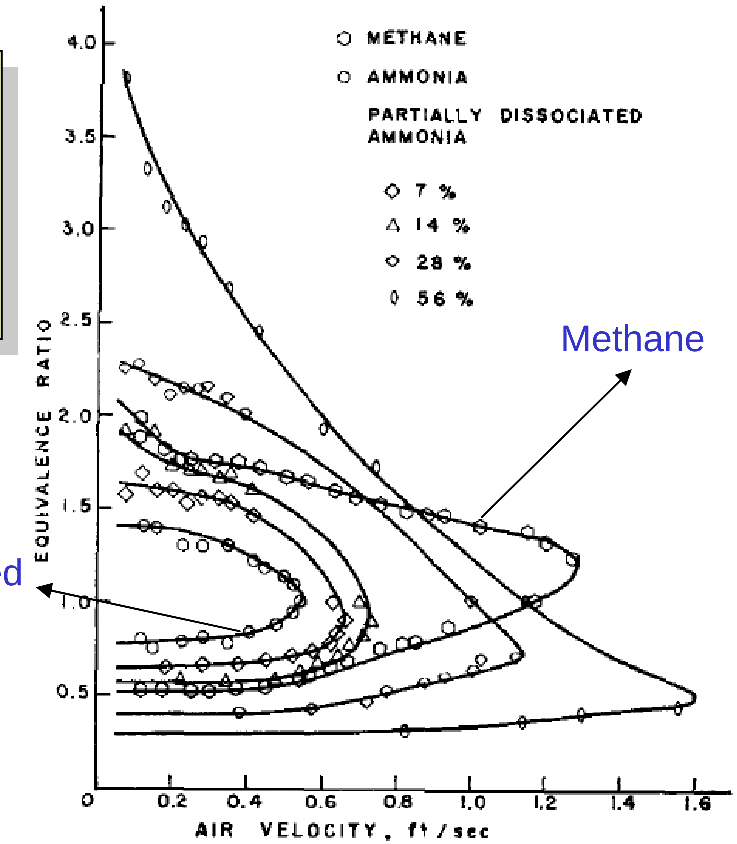
Why Crack?



Ref: Vercamp, Hardin and Williams

11th Symposium on Combustion

1967



- Uncracked NH3: Slow flame speed, large ignition energy, large quenching distance, poor flame stability
- Cracking is needed for 1) stability, 2) efficiency, 3) Low NOx emissions and 4) good power loading

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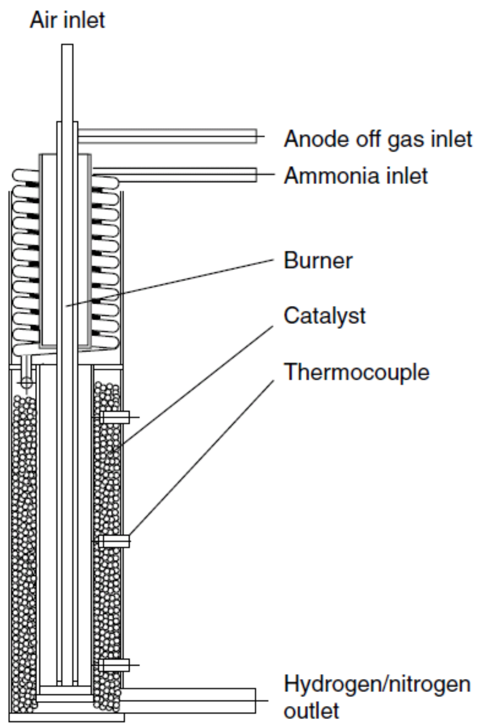
Fuel Conditioning: Partial Cracking of Ammonia

Autothermal Reformation of Ammonia

•These are designed for fuel cell applications

•Not suitable to gas turbines requiring high flow rate and small conversion rates



Ammonia cracker devised by Apollo Energy Systems

Off-the Shelf Crackers

- Thermal cracking method
- High temperature catalysts (800-900 C)
  - Expensive
  - Short life
- Large quantities of electric energy
- Heat losses
- Slow start up

Improved crackers:
Combustion with air over a catalyst bed

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Fuel Conditioning: Research

Pre-burner with O2

•Pursued by SPG

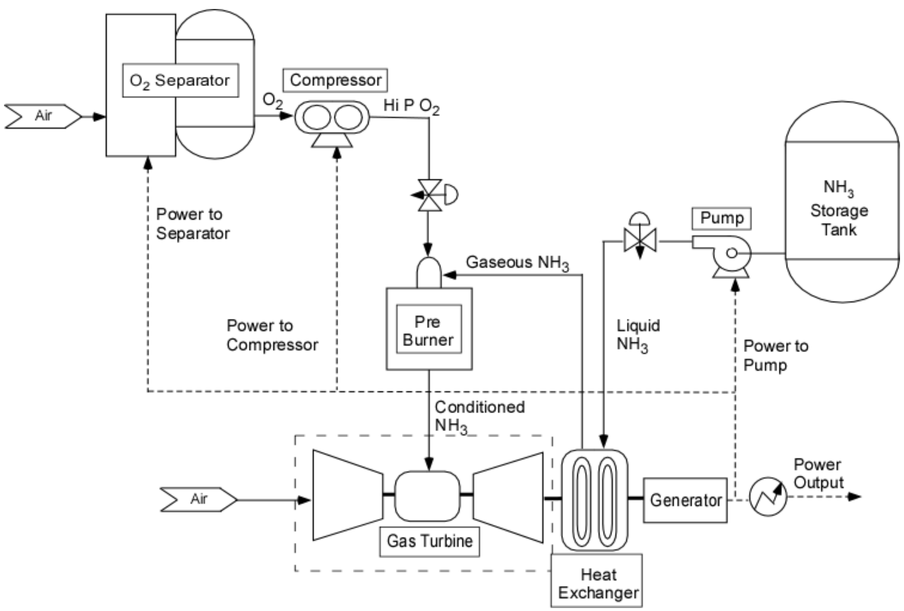
•Have small liquid rocket engine operating fuel rich

•Generate O2 if not available on site

•Pre-burn with NH3

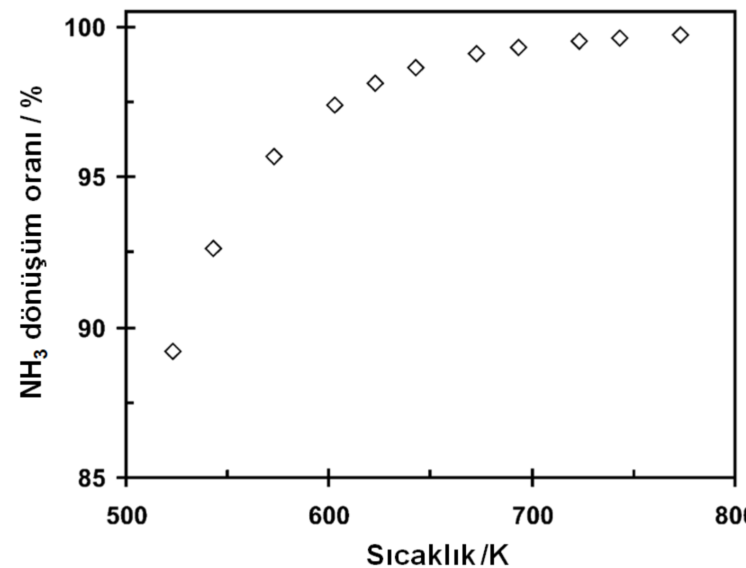
•Energy efficient process

•Not funded



Development of Low Temperature-Cost Effective Crackers

- Pursued by KOC University
- Working with a catalyst expert
- Well equipped University lab. available for development
- Possible funding: Turkish government



Thank You!