Ammonia as a hydrogen storage and the feasibility for internal combustion engines

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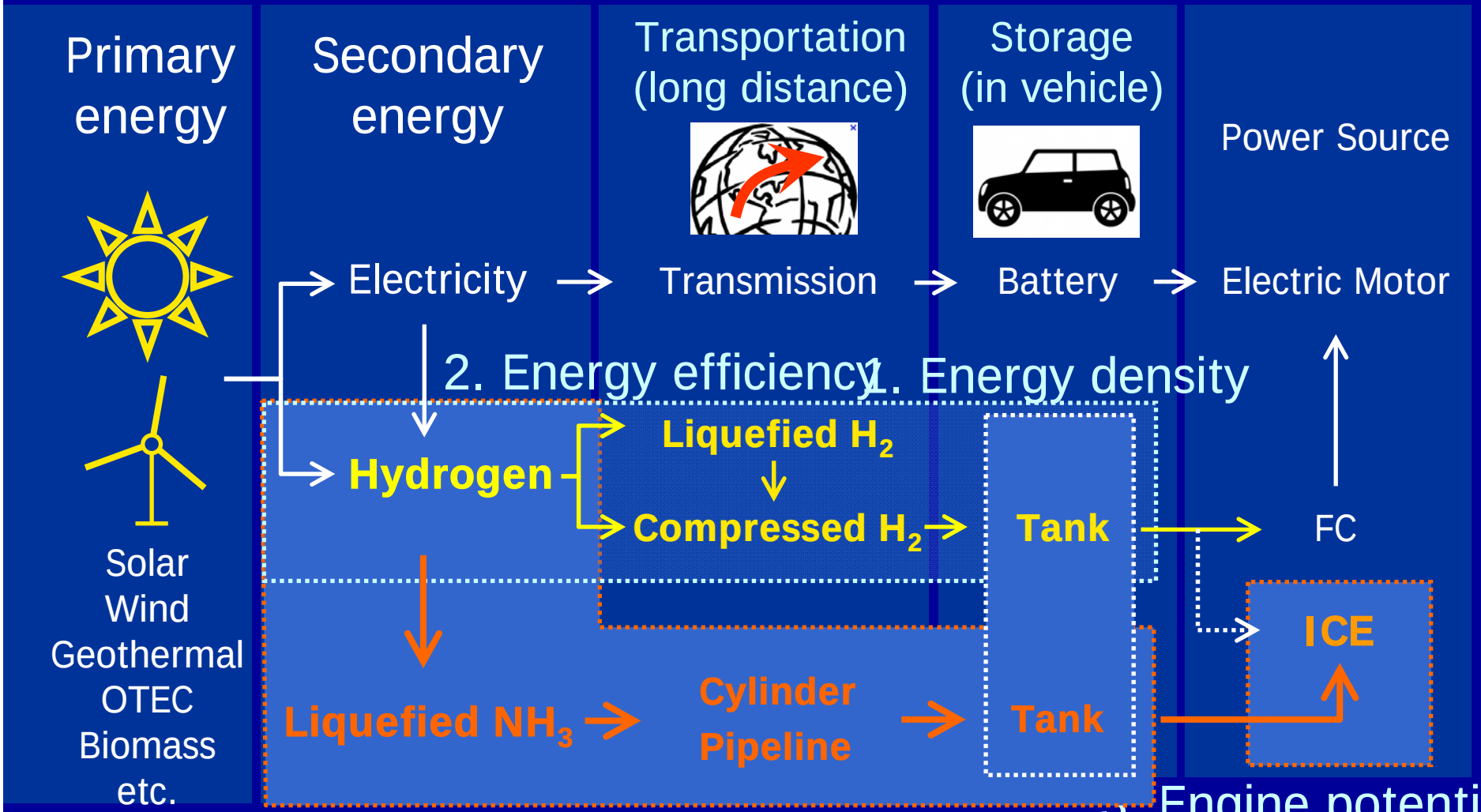
Sustainable energy flows for future vehicles

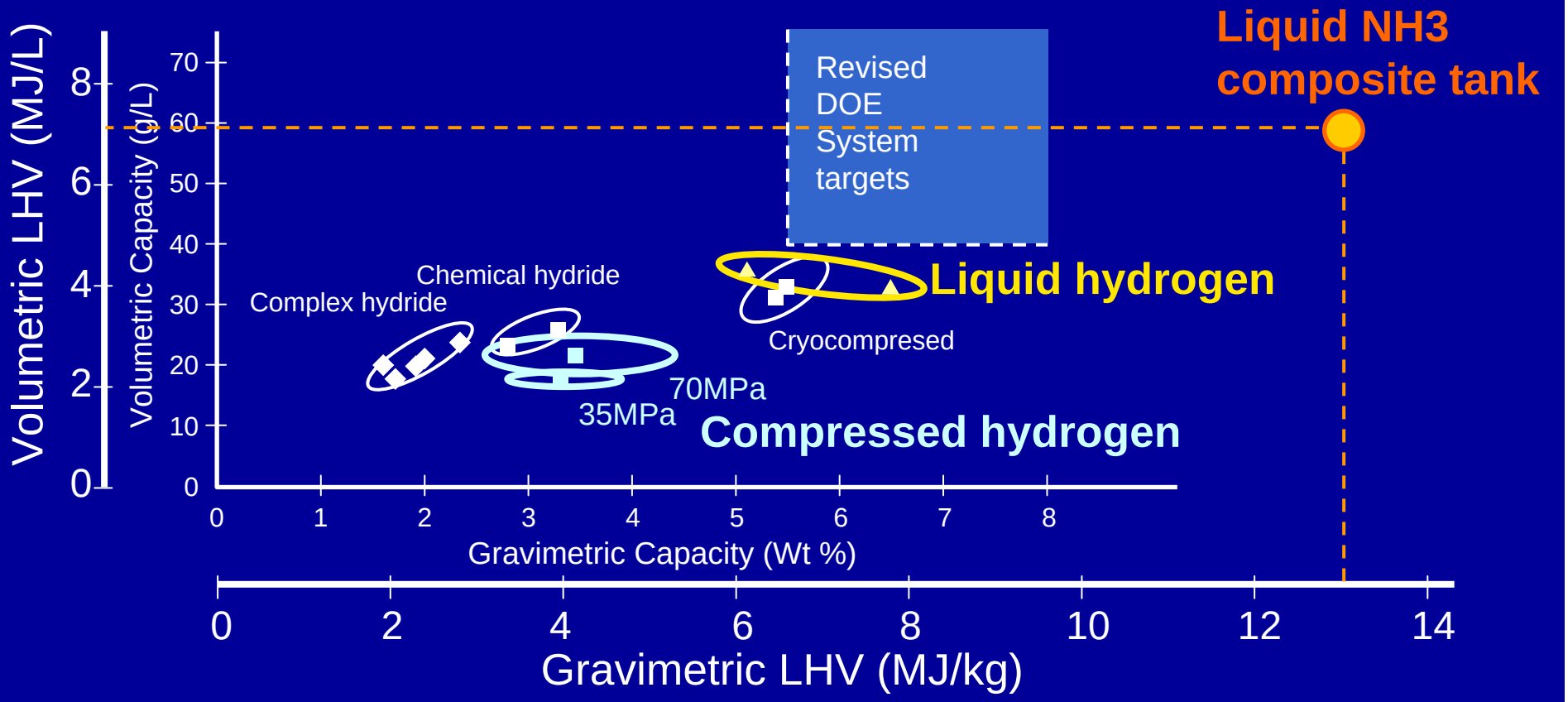


Energy density of storage

Liquid ammonia storage has 2-3 times higher energy density than current typical hydrogen storages.

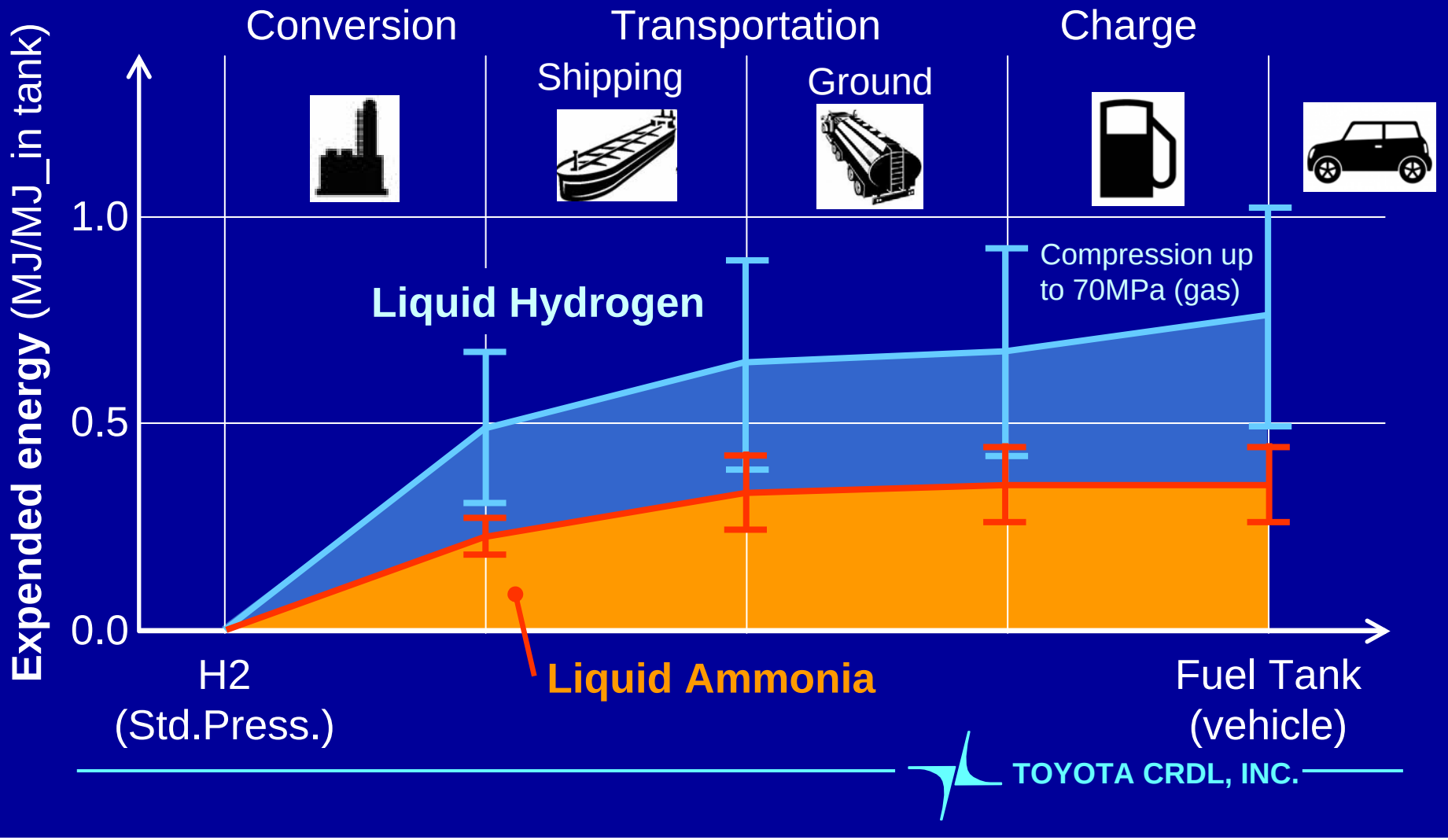
Status of hydrogen storage technologies

http://www1.eere.energy.gov/hydrogenandfuelcells/storage/tech_status.html



Expended energy in delivery

Hydrogen energy delivery in the form of liquid ammonia costs half of liquid hydrogen.



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Combustion properties of ammonia

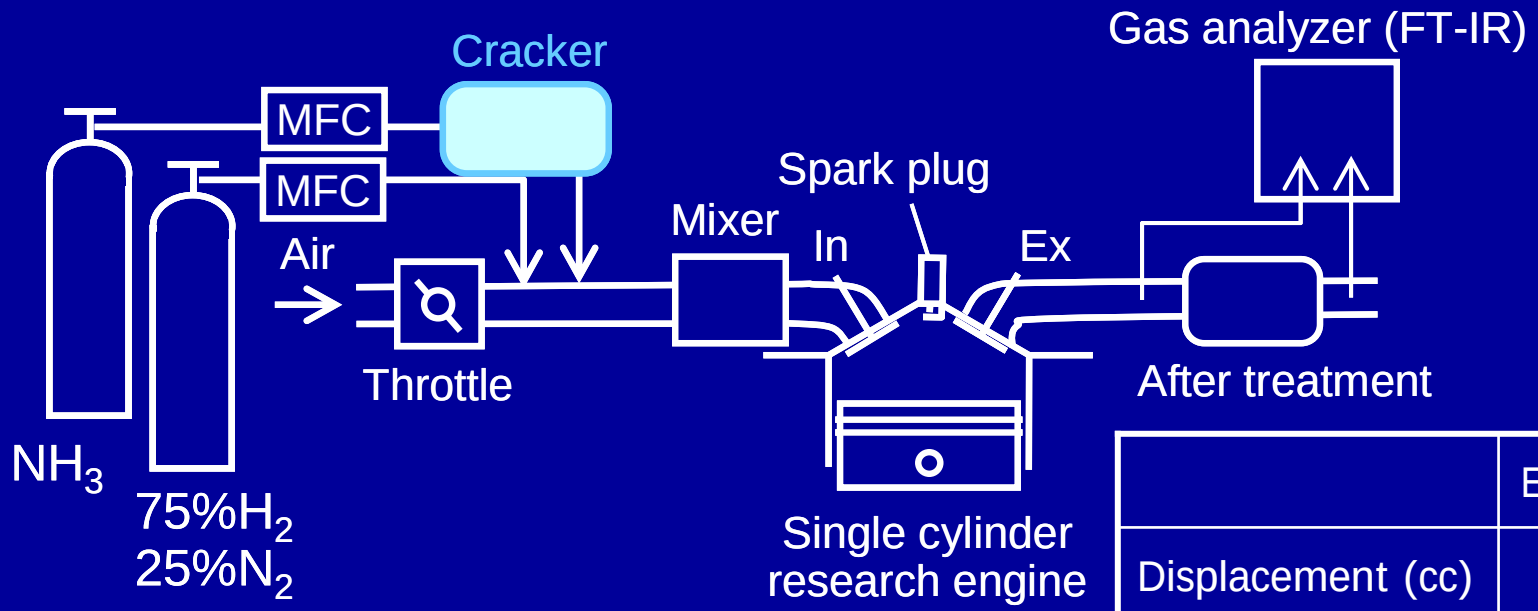
- Disadvantage
  - Low flame speed : Unstable engine operation
- Advantage
  - High ignition temperature : High knock tolerance

	Ammonia	Hydrogen	Gasoline
Laminar flame speed (cm/s)	**8**	**291**	**42**
Ignition temperature (K)	**924**	**853-873**	**573-773**
Heating value of mixture* (MJ/m3)	3.08	3.16	3.67
Flame temp. & Press. under constant volume combustion	2090K, 7.36atm	2390K, 6.87atm	2330K, 8.25atm

*stoichiometric mixture

Engine tests

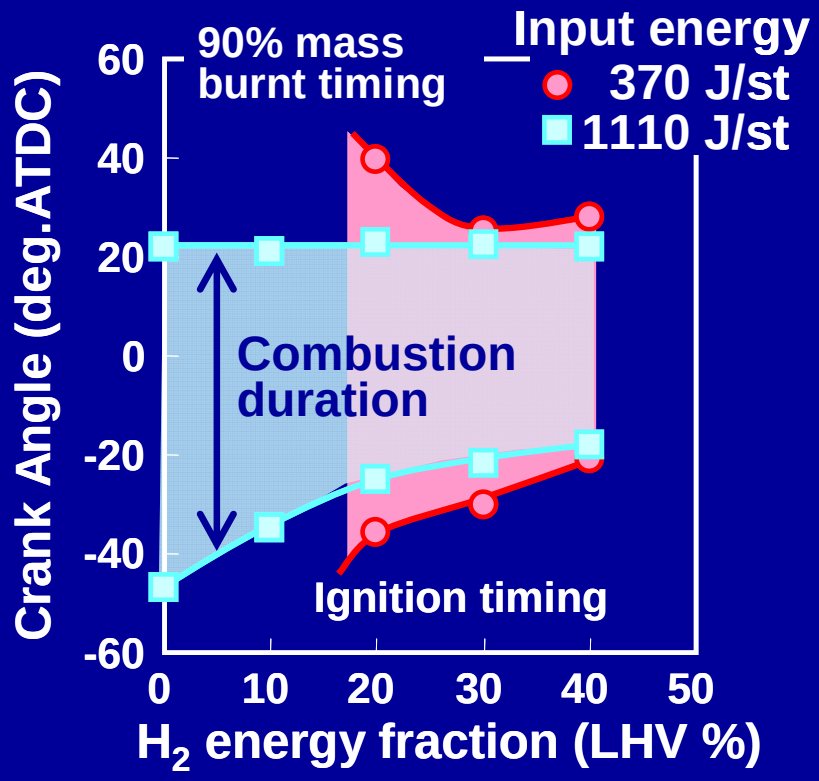
1. Stable operation conditions
2. On board ammonia cracking
3. High boosting & Large size engine



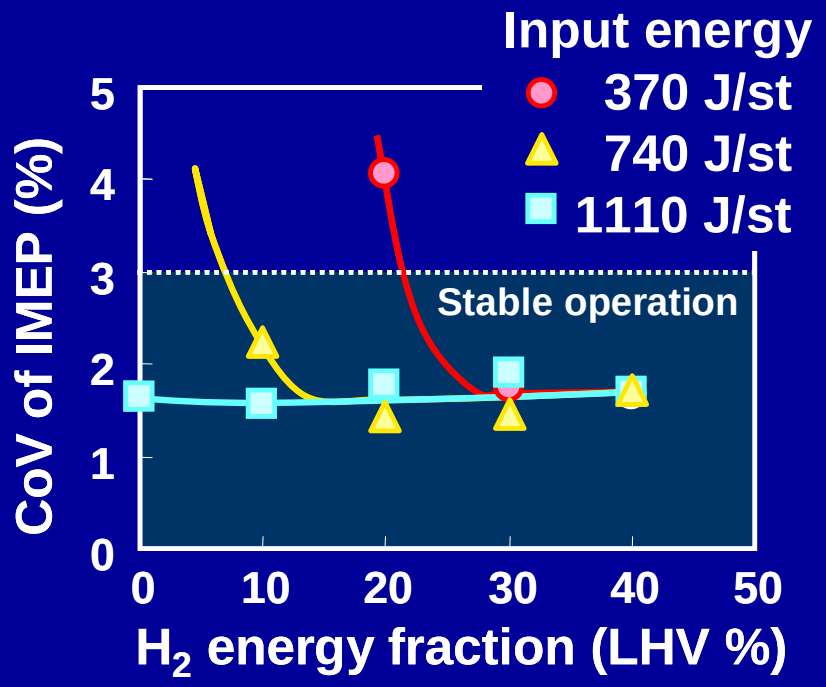
	Eng-1	Eng-2
Displacement (cc)	500	2147
Compression ratio	14	16

Stable operation with H2 addition

The lower hydrogen fraction is, the longer combustion duration is.
Hydrogen fraction for stable operation becomes low with increasing load.
At high load, pure ammonia can be burnt with sufficiently low cyclic variation.



Combustion duration (1200rpm)

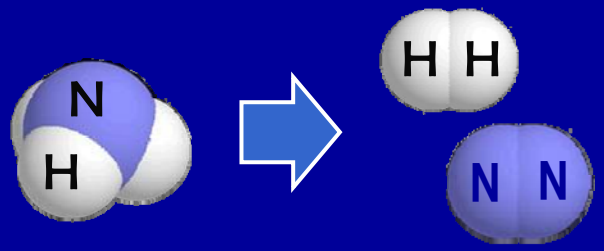


Stable operation condition (1200rpm)

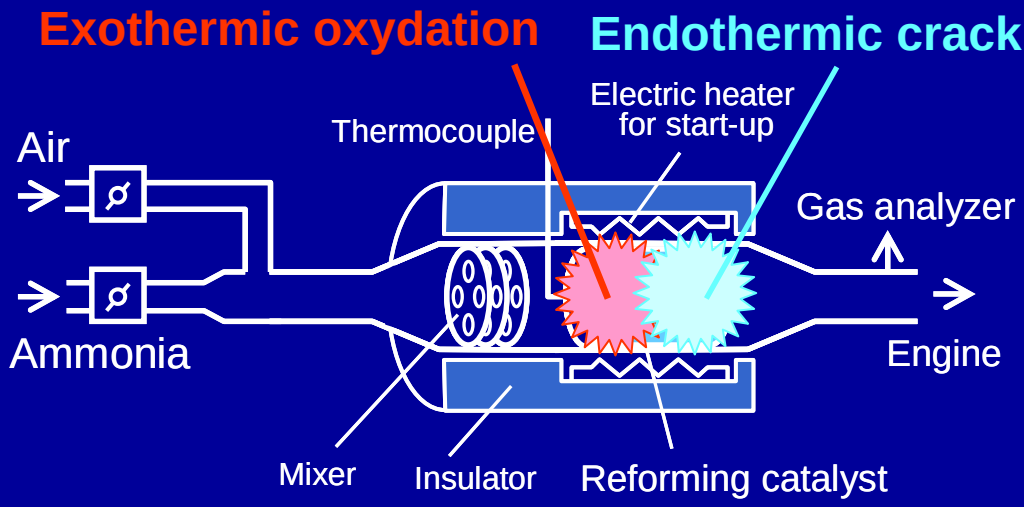
On board hydrogen production

Ammonia cracking

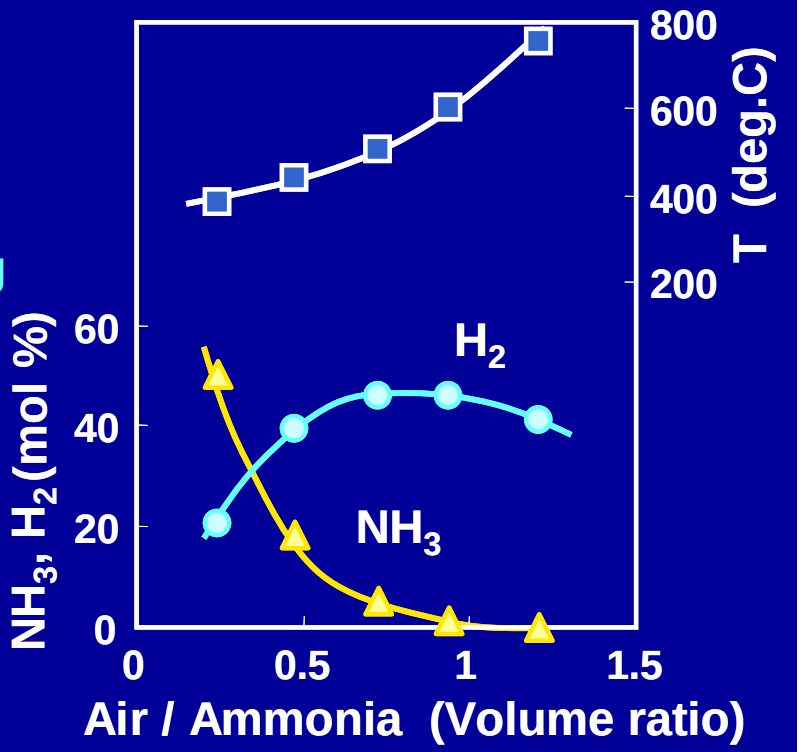
Endothermic reaction (40kJ/mol_NH3)



Auto thermal cracker (ATC)

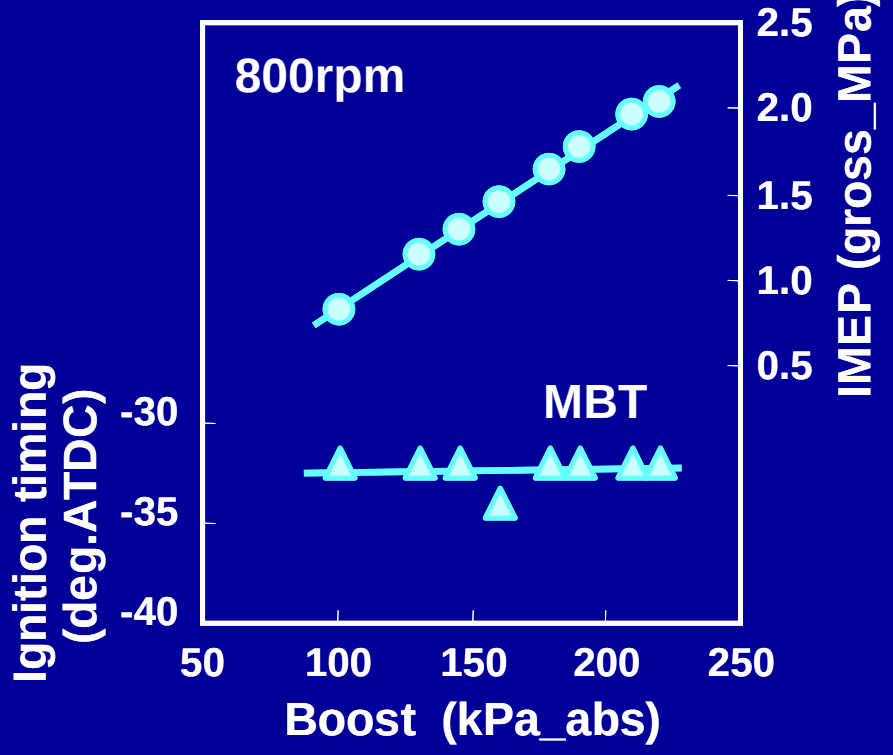


Hydrogen fraction can be controlled by changing air ratio.

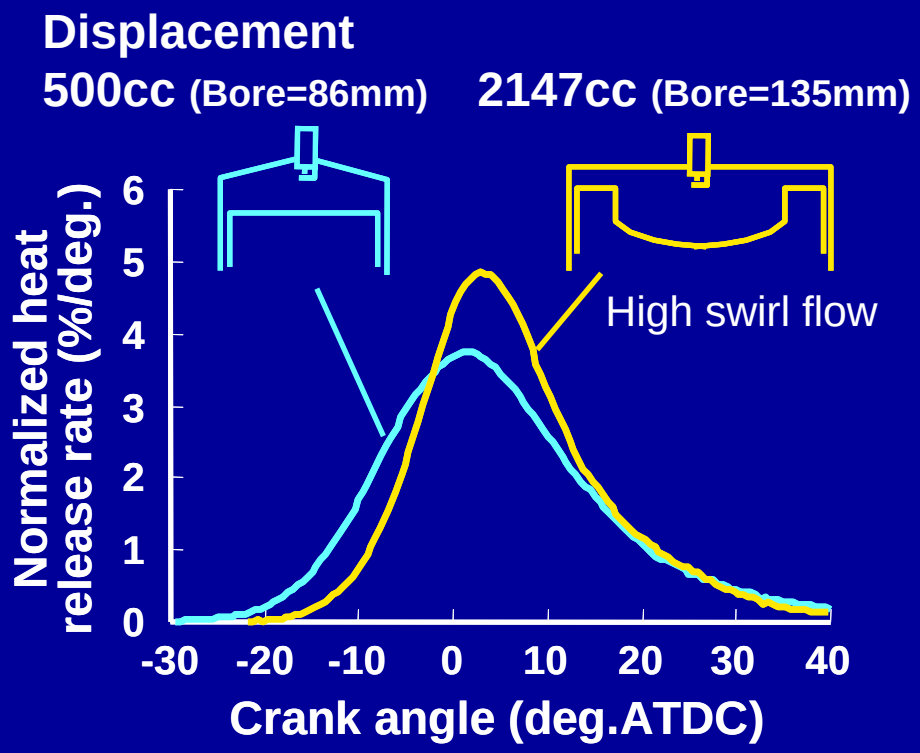


High boosting and large size engine

Ammonia fueled SI engine is free from knocking even under highly boosted condition as well as large bore size.



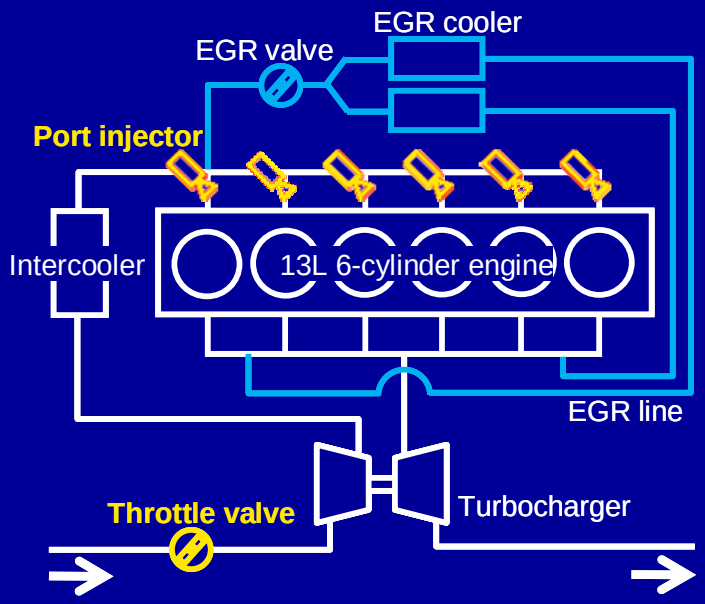
High boosting combustion



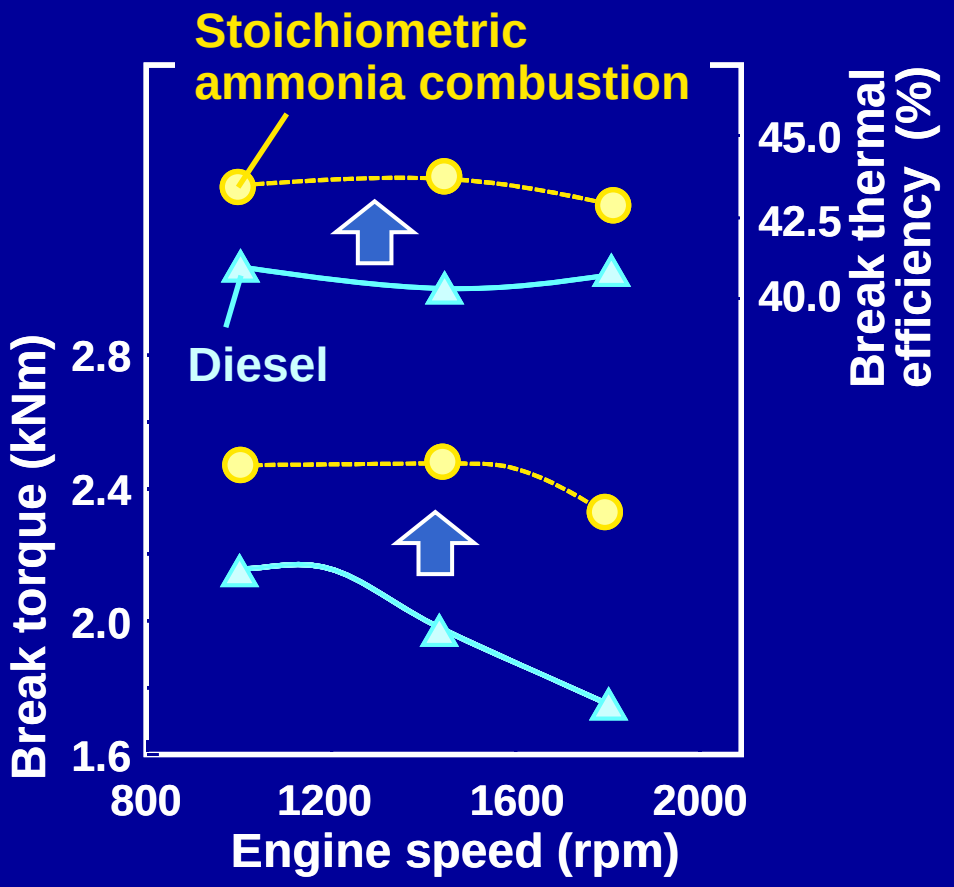
Effect of engine size
(1200rpm, 2.2kJ/st/L, pure ammonia)

Application for heavy duty trucks

Ammonia fueled SI engine is expected to show higher torque and thermal efficiency than current heavy duty diesel engine.



System simulation model



Prospect of engine performance

Conclusions

- **Liquid ammonia is feasible for vehicle fuel in the era of sustainable hydrogen society.**
  - **Liquid ammonia has twice higher energy density in storage and half expended energy in delivery compared with liquid hydrogen.**

- **Ammonia is applicable to spark ignition internal combustion engines.**
  - **Stable combustion is achieved by using auto thermal cracker which can control hydrogen fraction.**
  - **Pure ammonia is available at high load and overcomes knocking even under highly charged condition.**
  - **Ammonia fueled SI engine seems to be a good alternative for heavy duty diesel engines.**

Future challenges of ammonia ICE vehicles

- Cold start
  - Evaporation of ammonia
  - Stable engine operation
  - Emission control
- Improving combustion efficiency
  - Combustion enhancement at low hydrogen fraction
- Fueling system
  - Safety
  - Easy to handle
- Leak protection