# Development of Materials and Systems for Ammonia-Fueled Solid Oxide Fuel Cells

**Koichi Eguchi (Kyoto University),**
Yosuke Takahashi (Noritake), Hayahide Yamasaki (Nippon Shokubai),
Hidehito Kubo (Toyota Industries), Akihiro Okabe (Mitsui Chemical),
Takenori Isomura (Tokuyama), Takahiro Matsuo (IHI)

NH3 Energy+ - Enabling Optimized, Sustainable Energy and Agriculture
AIChE Minneapolis, USA
November 01, 2017,

# Ammonia as Hydrogen Carrier

## Hydrogen

- ✓ Primary fuel source for fuel cell
- ✓ Low volume density
- ✓ Difficulty in storage and transportation

## Ammonia

- ✓ High $H_2$ density
- ✓ Carbon-free
- ✓ High boiling point
- ✓ Ease in liquefaction and transportation
- ✓ Hydrogen production via decomposition reaction

$$NH_3 \rightarrow \frac{3}{2}H_2 + \frac{1}{2}N_2$$

$\Delta H^o = +46$ kJ mol$^{-1}$

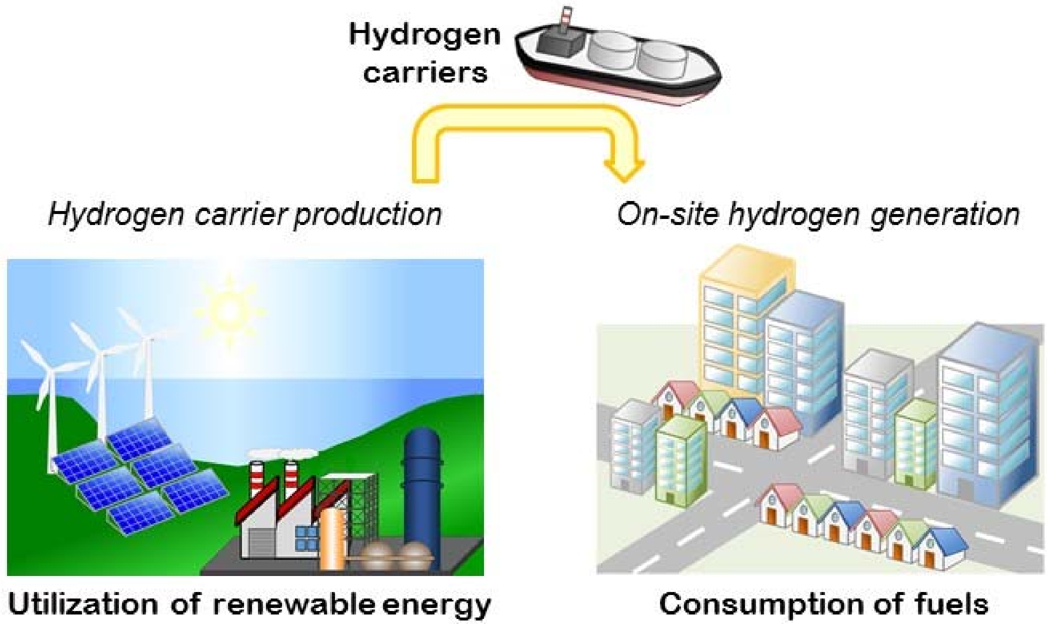
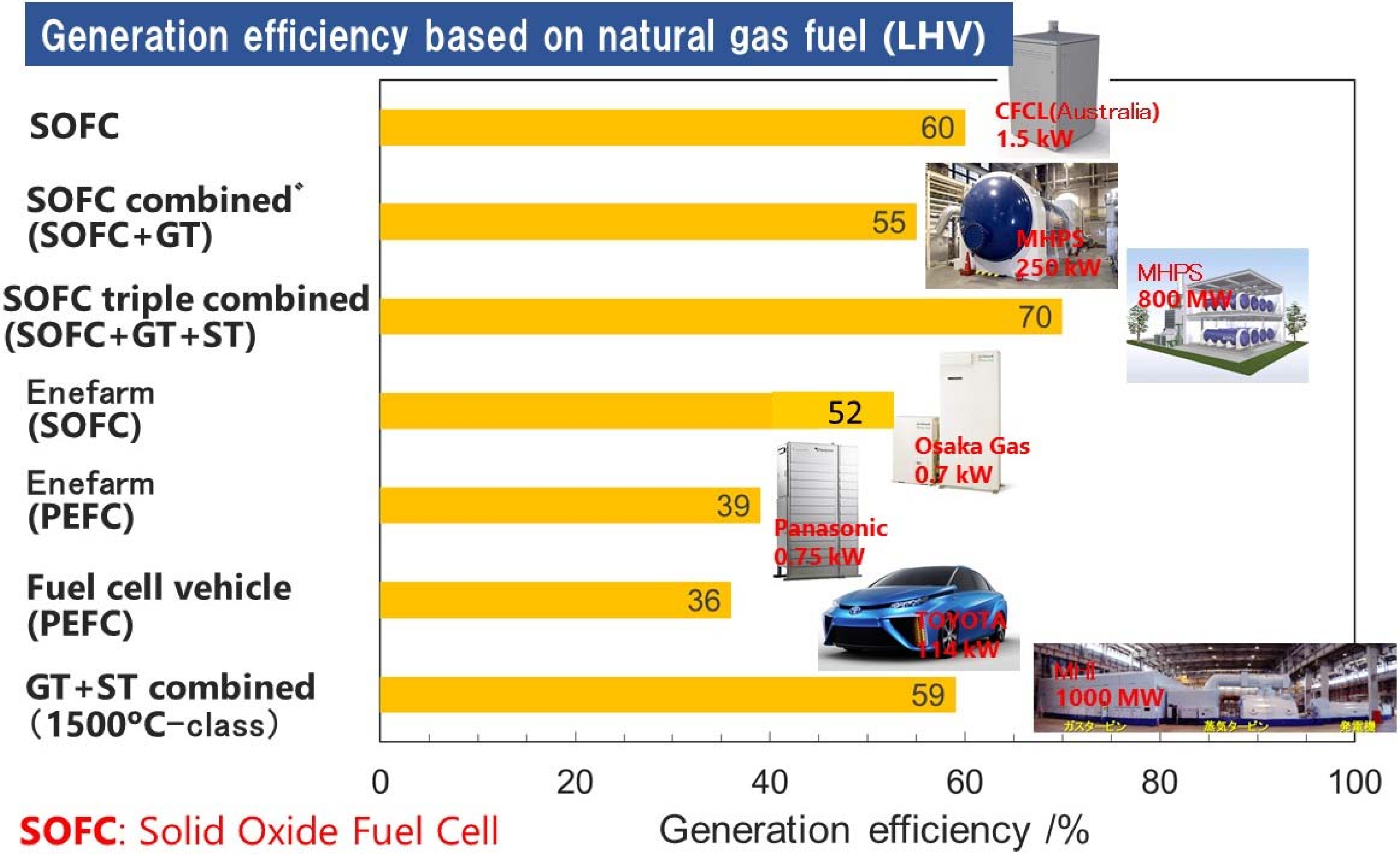



Table $H_2$ density and boiling point of liquid $H_2$, $NH_3$, and $C_7H_{14}$ (Methylcyclohexane)

| | $H_2$ density (kg-$H_2$ / m$^3$-liq.) | Boiling point (ºC) |
|---|---|---|
| Liquid $H_2$ | 70.8 | –252.6 |
| $NH_3$ | 120.3 | –33.3 |
| $C_7H_{14}$ (Methylcyclohexane) | 47.1 | 101.1 |

# comparison of generation efficiency




**SOFC**: Solid Oxide Fuel Cell

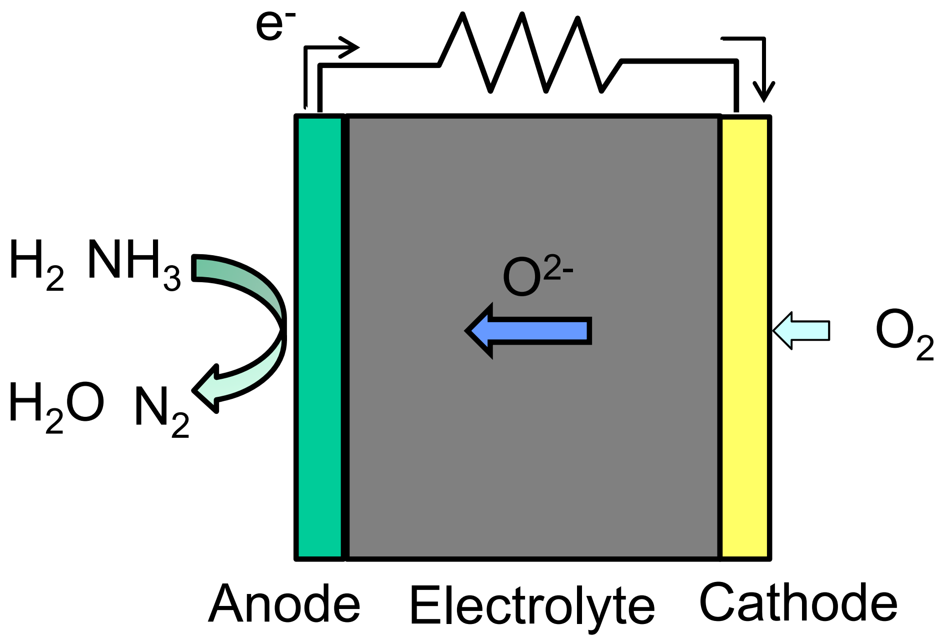
**PEFC**: Polymer Electrolyte Fuel Cell

**GT**: Gas Turbine

**ST**: Steam Turbine

**Cited from METI HP, HP Companies**

- Hydrogen-fueled SOFC
- Direct ammonia-fueled SOFC




$$2\ NH_3 \rightarrow N_2 + 3\ H_2$$

$$H_2 + O^{2-} \rightarrow H_2O + 2\ e^- \qquad 1/2\ O_2 + 2\ e^- \rightarrow O^{2-}$$

# Hydrogen carrier & energy conversion technology

Kyoto Univ.

- Ammonia as a promising hydrogen carrier:

*High $H_2$ density, Carbon-free, Low production cost, High boiling point, Ease in liquefaction and transportation, etc.*

| | $H_2$ density (kg-$H_2$ / $m^3$-liq.) | Boiling point (ºC) | $\Delta H_r$ (kJ/mol-$H_2$) |
|---|---|---|---|
| Liquid $H_2$ | 70.8 | –252.6 | – |
| $NH_3$ | 120.3 | –33.3 | 30.6<br>$2NH_3 \rightarrow N_2 + 3H_2$ |
| $C_7H_{14}$ (Methylcyclohexane) | 47.1 | 101.1 | 80.0<br>$C_7H_{14} \rightarrow C_7H_8 + 3H_2$ |

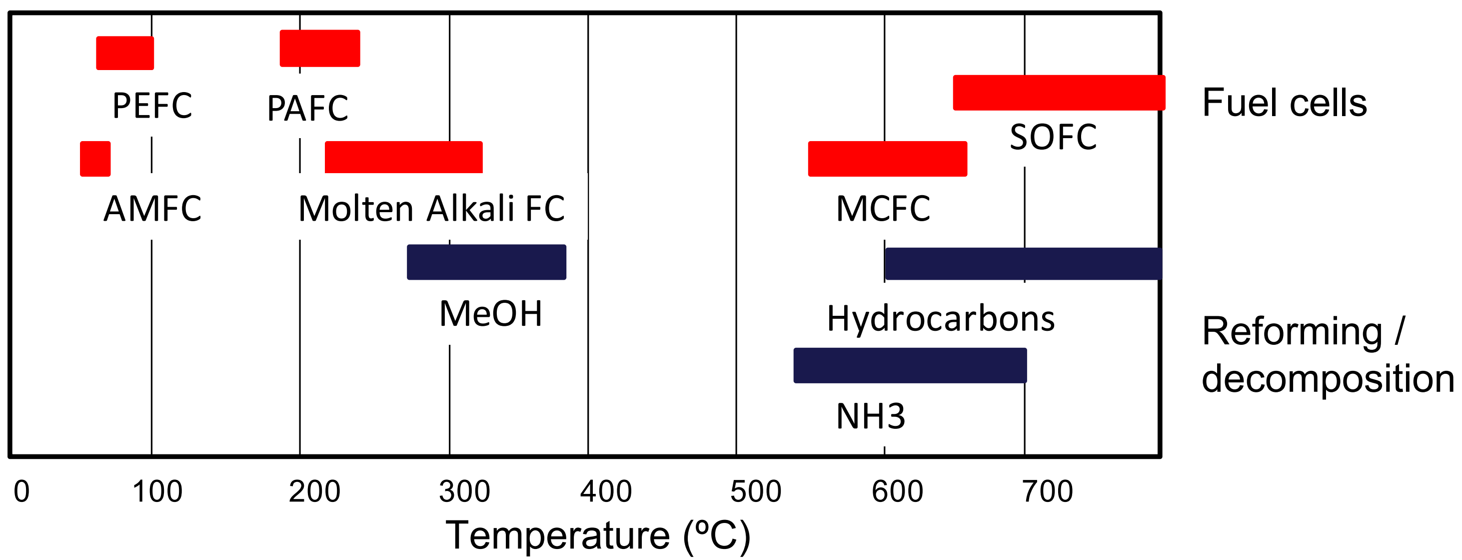
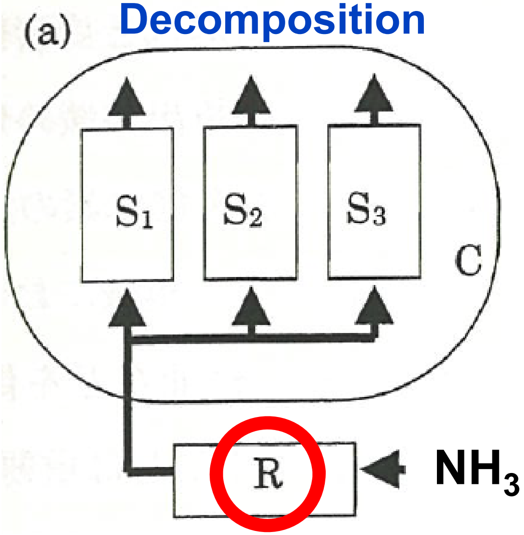



Fig. Operating temperature ranges of fuel cells and catalytic reformers

# Operation type of ammonia fueled cell

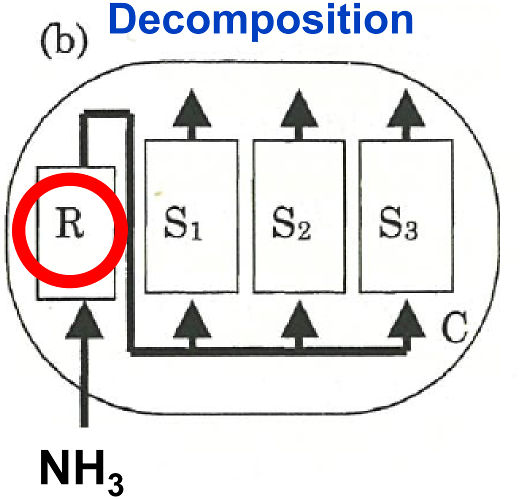
R: $NH_3$ decomposition reactor, C:Fuel cell chamber, S:SOFC stack

### External Decomposition



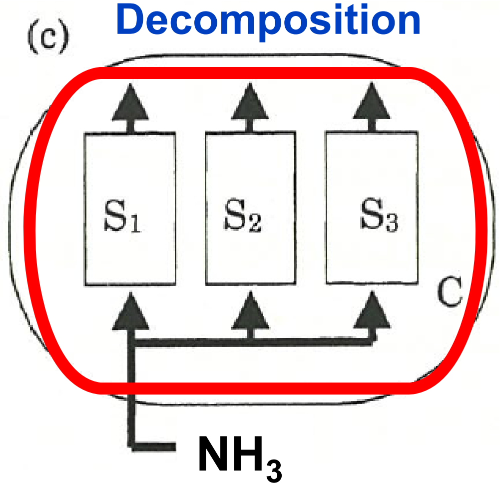

- $NH_3$ decomp. reactor installed on the flow line
- Optimized operation of each reactor
- Large energy loss
- Large system size
- Stationary application

### Indirect Internal Decomposition




- Reactor installed in the FC chamber
- System design with effective heat management
- Either stationary or mobile application

### Direct Internal Decomposition




- $NH_3$ decomp. reactor unnecessary
- $NH_3$decomp. And anode reaction proceed on the electrode
- Simplified system
- Multifunctional electrode
- Heat management
- Either stationary or mobile application

# Durability of Catalyst for $NH_3$ Cracking

**Catalyst:** 5wt.% SrO–40wt.% $Ni/Y_2O_3$ (Pretreated at 600ºC in 50%$H_2$/Ar)
**Supply gas:** 100% $NH_3$; Space velocity = 2,400 $h^{-1}$
**Durability test:** 700ºC
**Activity evaluation:** 515ºC, 565ºC

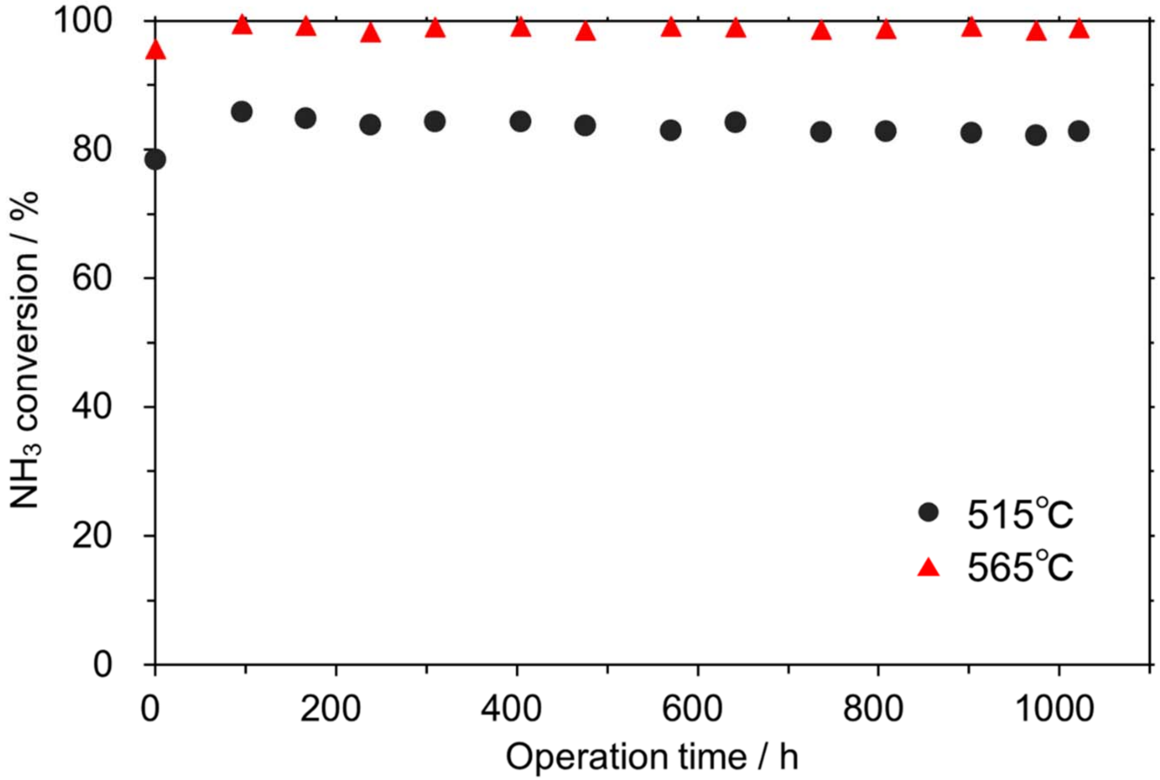
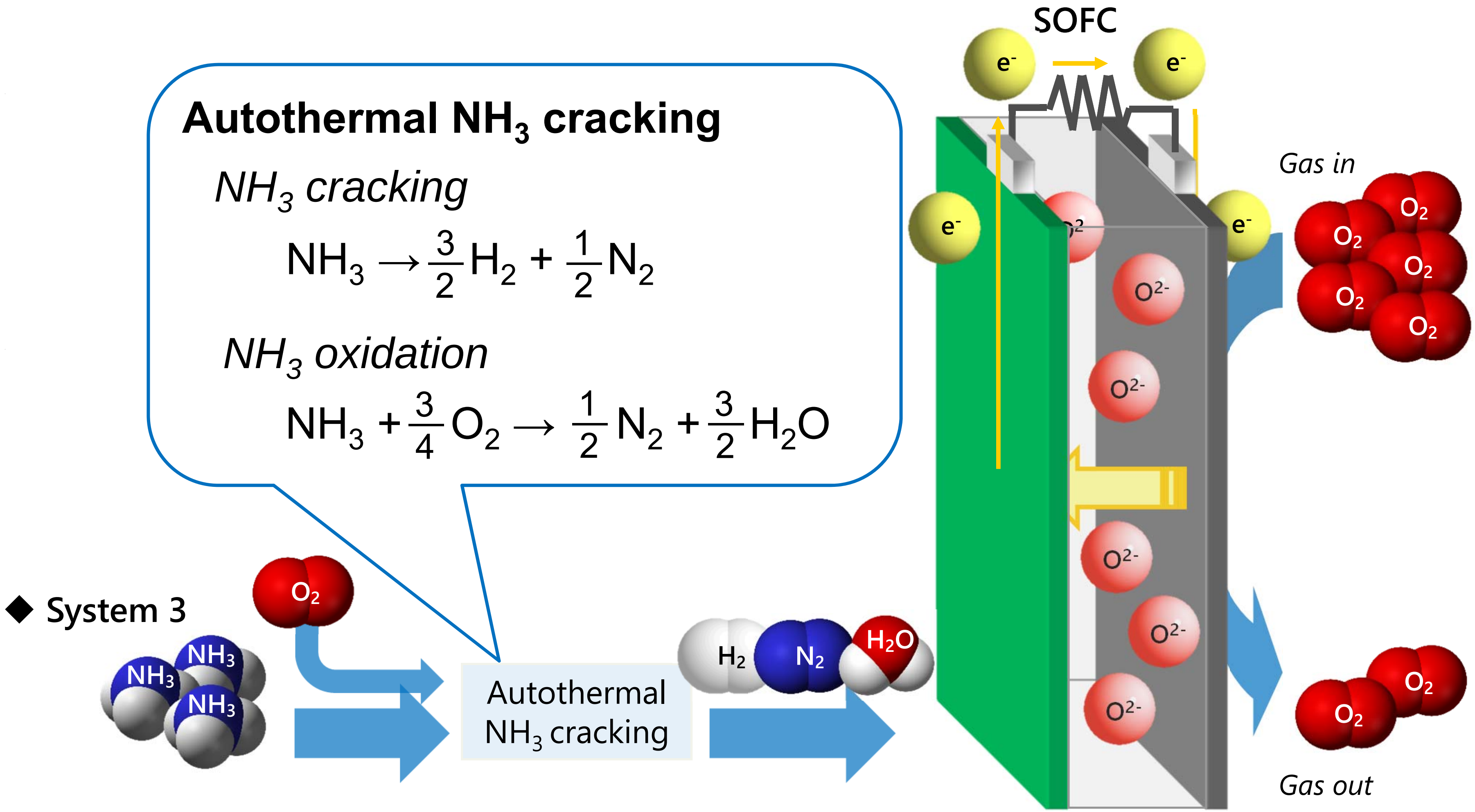


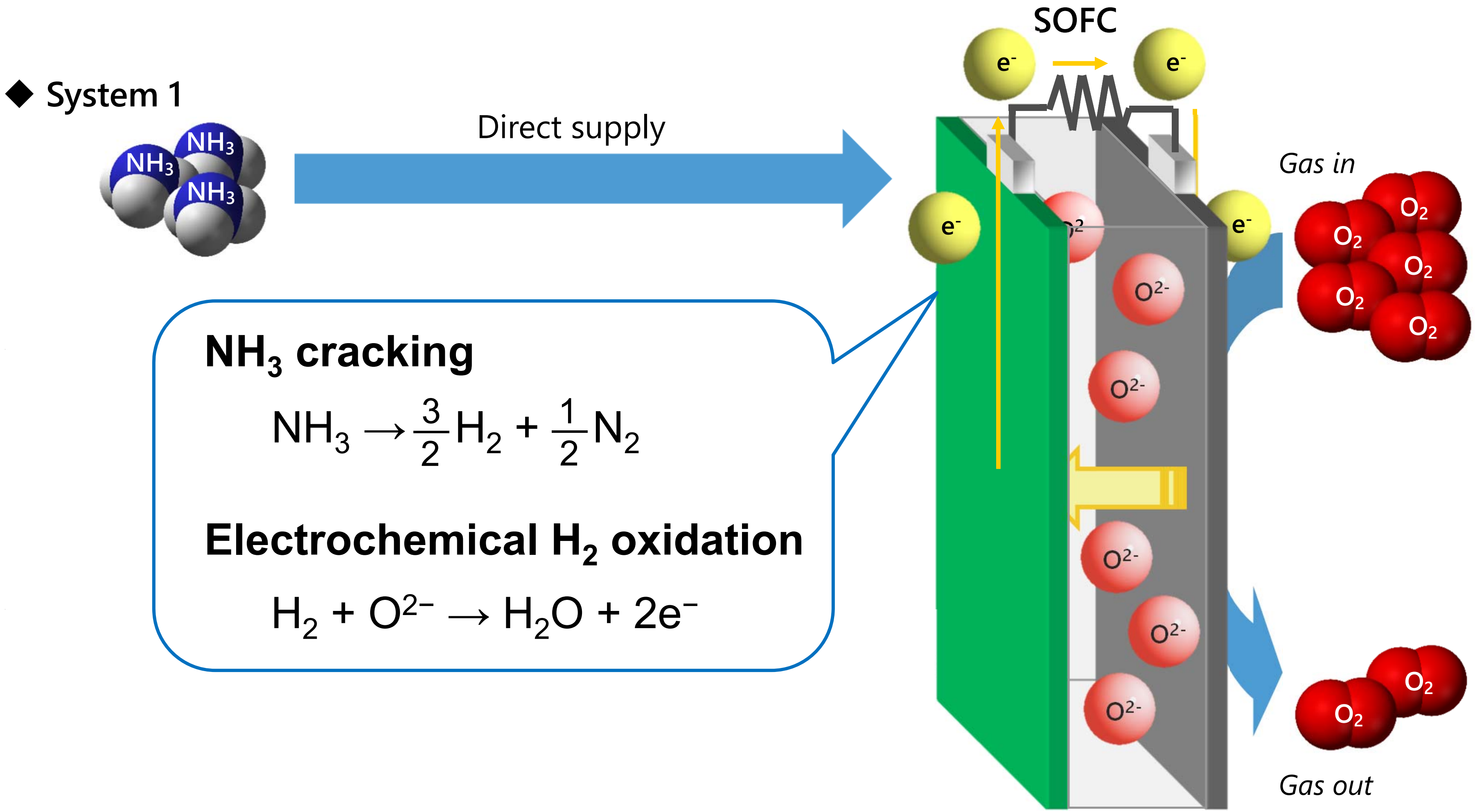

Fig. Time course of ammonia conversion at 515 and 565ºC for the SrO–$Ni/Y_2O_3$ catalyst under the stability test at 700ºC with an S.V. of 2,400 $h^{-1}$.

# Ammonia-fueled Solid Oxide Fuel Cell System




It is important to develop the catalyst and control the reaction conditions !!

# Ammonia-fueled Solid Oxide Fuel Cell System




**$NH_3$ cracking**

$$NH_3 \rightarrow \frac{3}{2}H_2 + \frac{1}{2}N_2$$

**Electrochemical $H_2$ oxidation**

$$H_2 + O^{2-} \rightarrow H_2O + 2e^-$$

# Cell & Material

Table Configuration of the anode-supported cell

| Layer | Composition | Thickness / μm | Diameter / mm |
|---|---|---|---|
| Anode support layer | NiO/$ZrO_2$-based material | 1000–1100 | 120 |
| Anode functional layer | NiO/$ZrO_2$-based material | 7–13 | 120 |
| Electrolyte layer | $ZrO_2$-based material | 7–13 | 120 |
| Cathode layer | Perovskite-type oxide material | 30–90 | 110 |

# Performance of $NH_3$-fueled SOFC Stack with 10 single cells

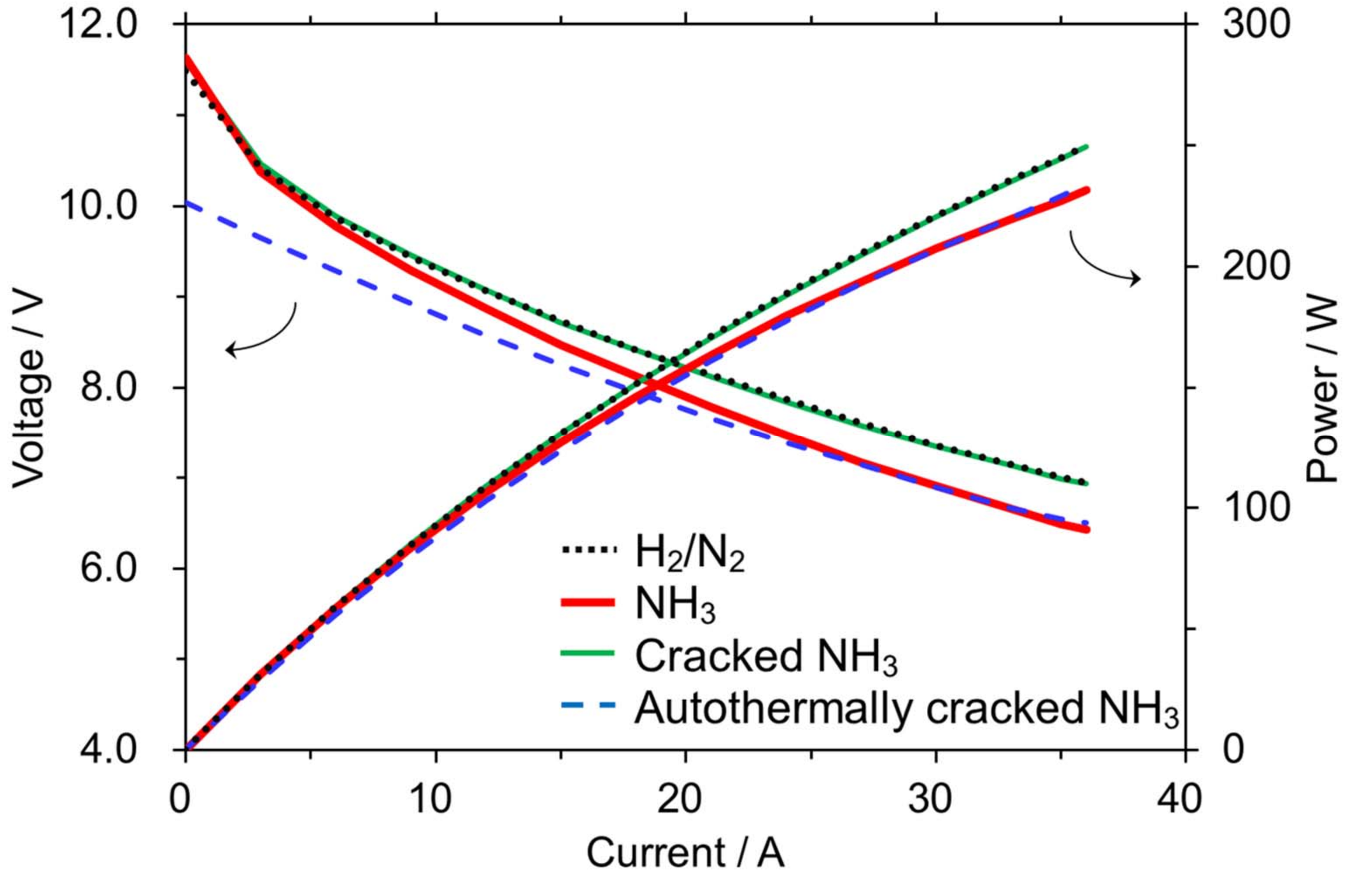



Fig. *I–V* and *I–P* characteristics of the SOFC stack at 770ºC. Anode gas: 75% $H_2$–25% $N_2$, $NH_3$, cracked $NH_3$, and autothermally cracked $NH_3$; Cathode gas: Air.

## Summary

- ✓ The rapid start-up less than 130 sec was possible with the autothermal $NH_3$ cracker.
- ✓ The SOFC stack with 30 single cells fueled with $NH_3$ exhibited 1 kW power at ca. 750ºC.
- ✓ The DC generation efficiency of 1 kW class SOFC stack was 50% or higher.

## Acknowledgment

This work was supported by the Council for Science, Technology and Innovation (CSTI) Cross-ministerial Strategic Innovation Promotion Program (SIP) “energy carrier” (Funding agency: JST).