SYNERGISTIC HYDROGEN PRODUCTION BY NUCLEAR-HEATED STEAM REFORMING OF FOSSIL FUELS

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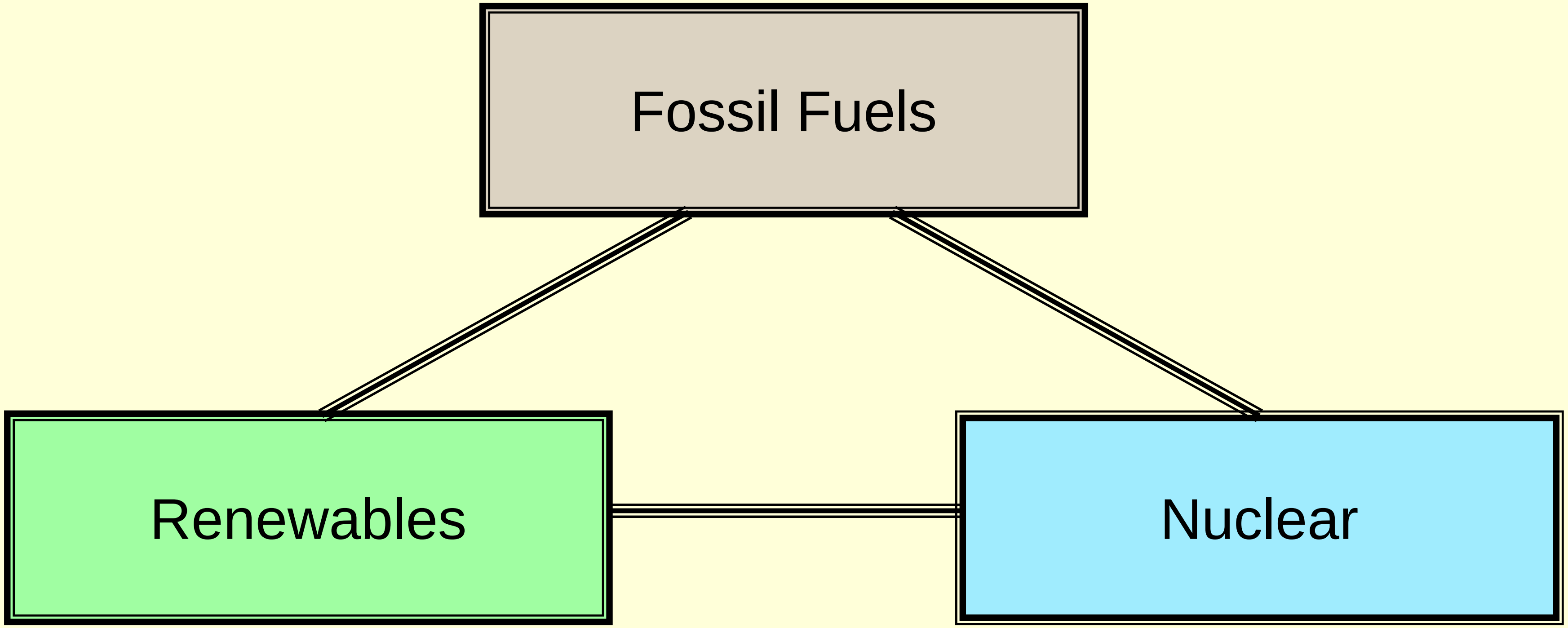
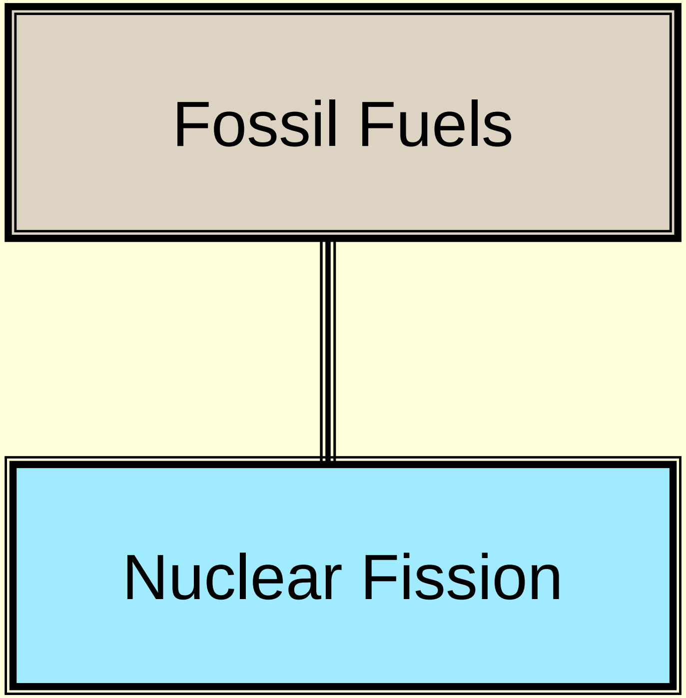
Hydrogen Production
From Various Primary Energy Sources

Fossil Fuels	**Natural gas, Petroleum, Coal, etc.** *Chemical energy, Heat, Electricity*
Nuclear	**Fission, Fusion, Waste, etc.** *Heat, Radiation, Electricity*
Renewables	**Solar, Wind, Hydro, Biomass, etc.** *Heat, Light, Power, Chemical energy, Electricity, etc.*

Hydrogen Production
By Synergy among Energies



Fossil Fuels + Nuclear Fission
Synergistic Hydrogen



Rich and Inexpensive in;

Chemical bonding energy

Rich and Inexpensive in;

Heat

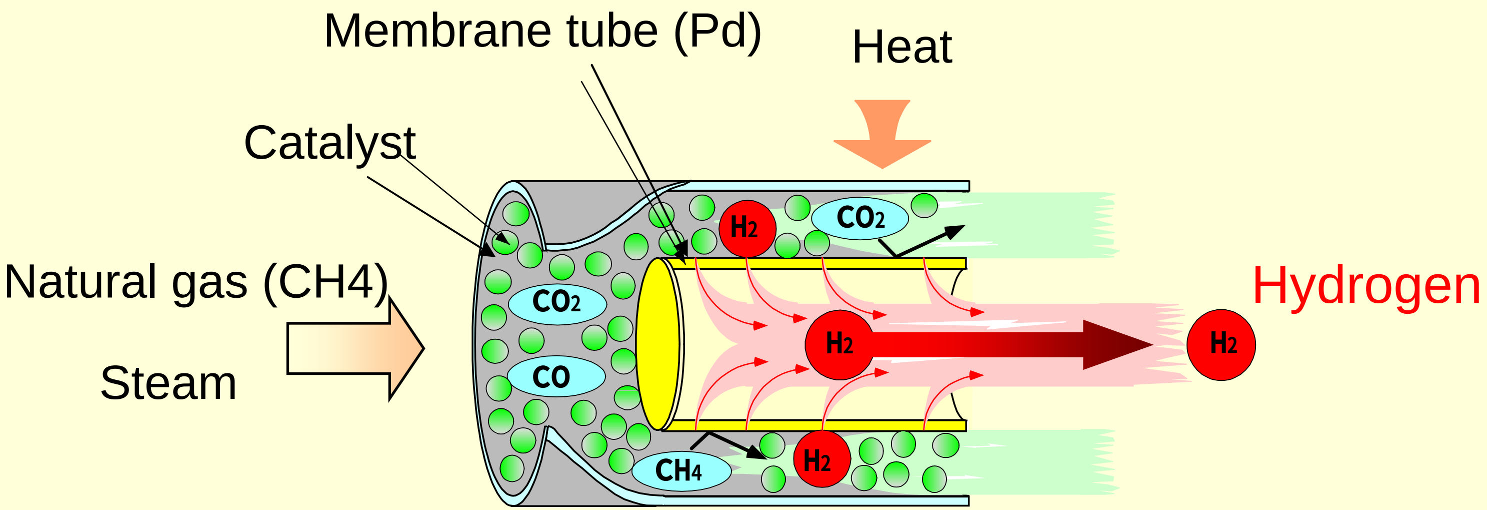
Fossil Fuels – Nuclear Synergistic Hydrogen

- Fossil Fuels
  - Natural Gas (Methane)
  - Petroleum (LPG, Naphtha, Kerosene)
  - Coal
- Nuclear Heat
  - High Temperature (HTGR, LMR)
  - Medium Temperature (SFR)
  - Low Temperature (LWR, HWR)
- Reaction
  - Steam Reforming (Methane)
  - Steam Gasification (Coal)

Medium Temperature Steam Reforming

- Reaction Process = Membrane Reforming
- Heat = Sodium Cooled Nuclear Reactor
- Reactants = Fossil Fuels + Water
  - Natural Gas (Methane)
  - Petroleum (LPG, Naphtha, Kerosene)
  - Coal
- Products = H_2 + CO_2

Membrane Reforming
-- Principle and Features --



Steam reforming reaction

$CH_4 + H_2O \rightleftharpoons CO + 3H_2$

Separation

Shift reaction

$CO + H_2O \rightleftharpoons CO_2 + H_2$

Separation

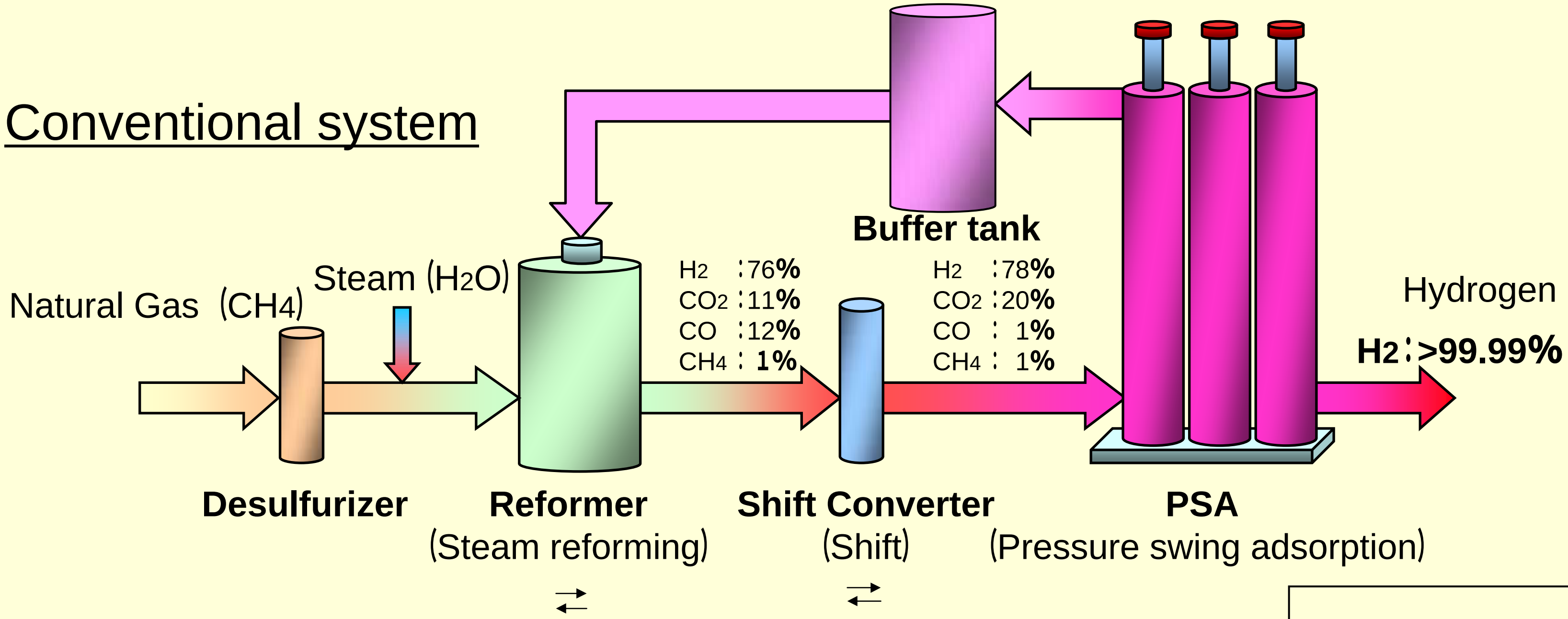
Features

- Free from limitation by chemical equilibrium
- Acceleration of steam reforming reaction by separating hydrogen selectively using palladium membranes
- Lowering reaction temperature from 800ºC to 500-600ºC
- Production of pure hydrogen

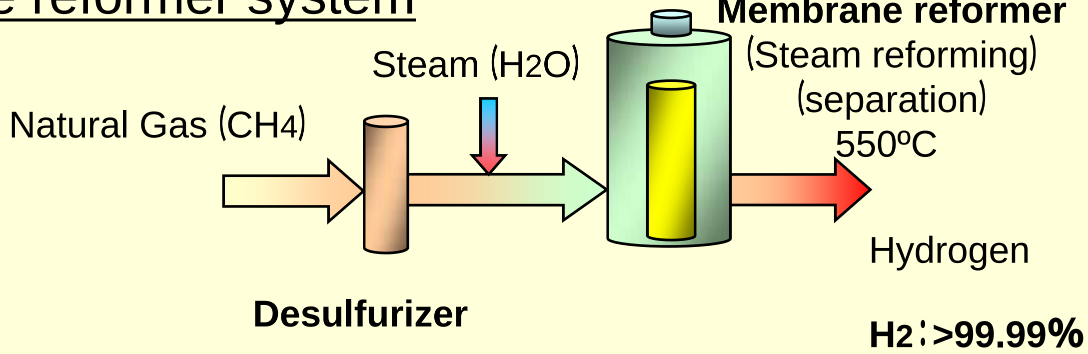
Source: Tokyo Gas Co.

Conventional System & Membrane Reformer System

Conventional system



Membrane reformer system



- compact
- simple
- high efficiency

Source: Tokyo Gas Co.

Merits of Membrane Reformer

- By the simultaneous generation and separation of hydrogen, the membrane reformer system can be much more compact and can provide higher efficiency than the conventional ones.
- The simultaneous progress of hydrogen generation and separation makes the reaction free from the limitation of chemical equilibrium, thus can lower the reaction temperature down to 500~600 degree Celsius.
- This gives benefits of avoiding use of expensive heat-resistant materials and increased long-term durability.

Hydrogen Station Operating in Senju Tokyo

Membrane Reformer by Tokyo Gas Co.
Volume=1/3 Space=1/2 as Compared with the Conventional Reformer

Advantageous Effects of Nuclear-Heated Recirculation-Type Membrane Reformer

1. Advantageous effect of nuclear heat supply for the endothermic heat of reforming reaction, thus reducing the fuel consumption to be used for the heating
2. Advantageous effect of re-circulating the reaction products through a closed loop configuration while separating H_2 and CO_2, thus reducing surface area of Pd membrane modules

Reaction Formulas of Steam Reforming of Natural Gas (CH_4) to Produce Hydrogen

Reforming reaction;

$$CH_4 + H_2O = CO + 3H_2 \qquad - 206 \text{ kJ/mol}$$

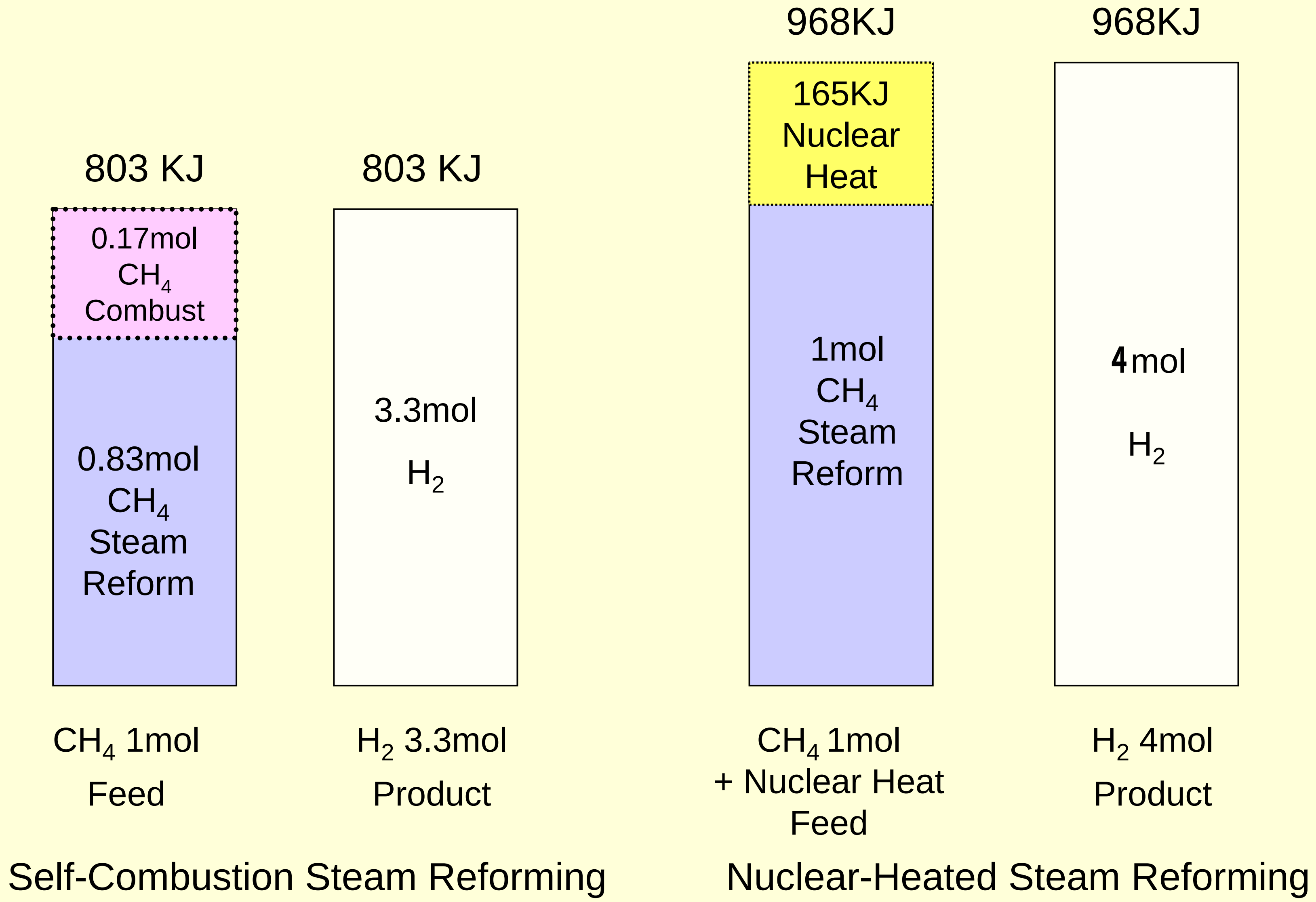
Shift reaction;

$$CO + H_2O = CO_2 + H_2 \qquad + 41 \text{ kJ/mol}$$

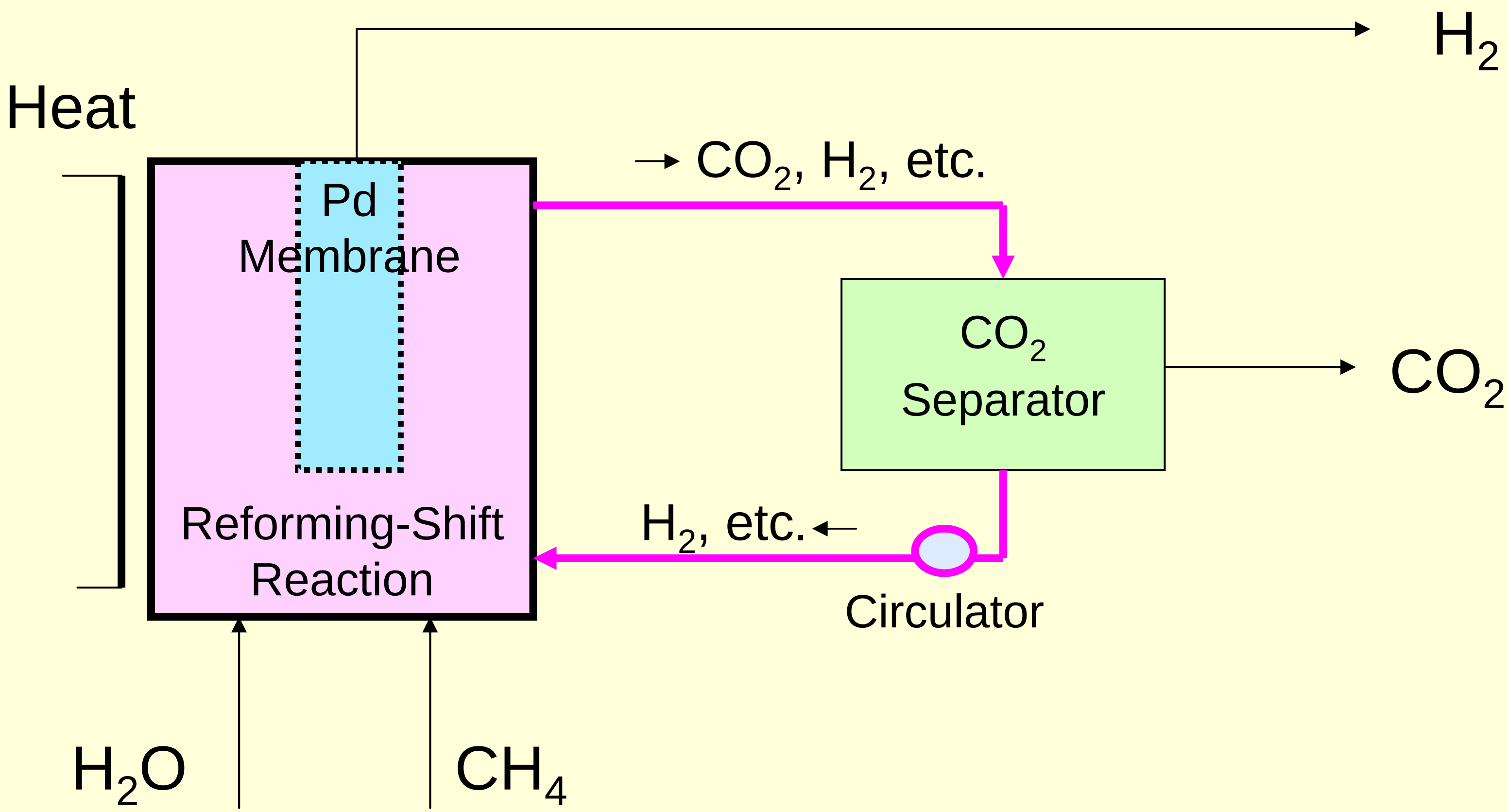
Reforming-shift reaction;

$$CH_4 + 2H_2O = CO_2 + 4H_2 \qquad -165 \text{ kJ/mol}$$

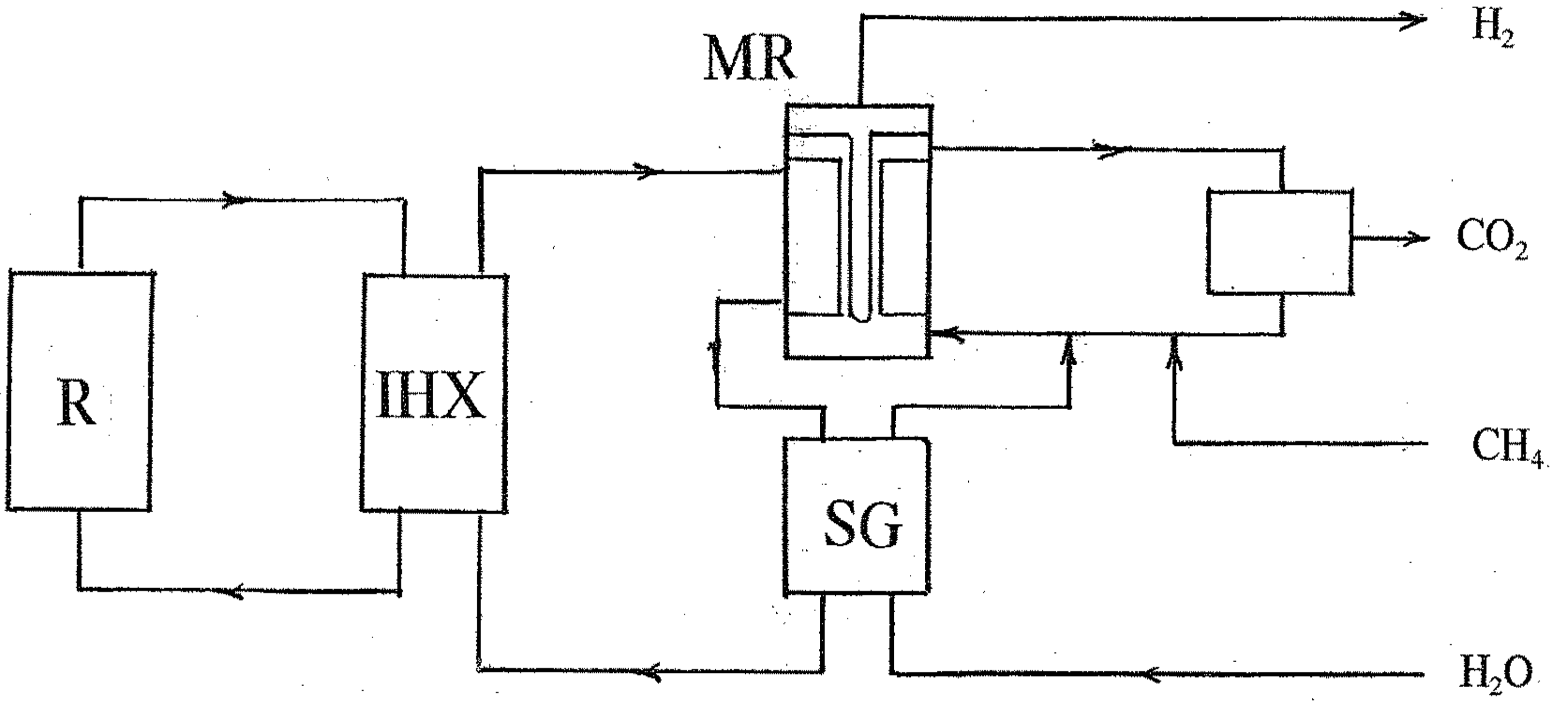
Advantageous Effect of Nuclear Heat Supply To Steam Methane Reforming



Recirculation Type
Membrane Reformer



Nuclear-Heated Recirculation-Type Membrane Reformer



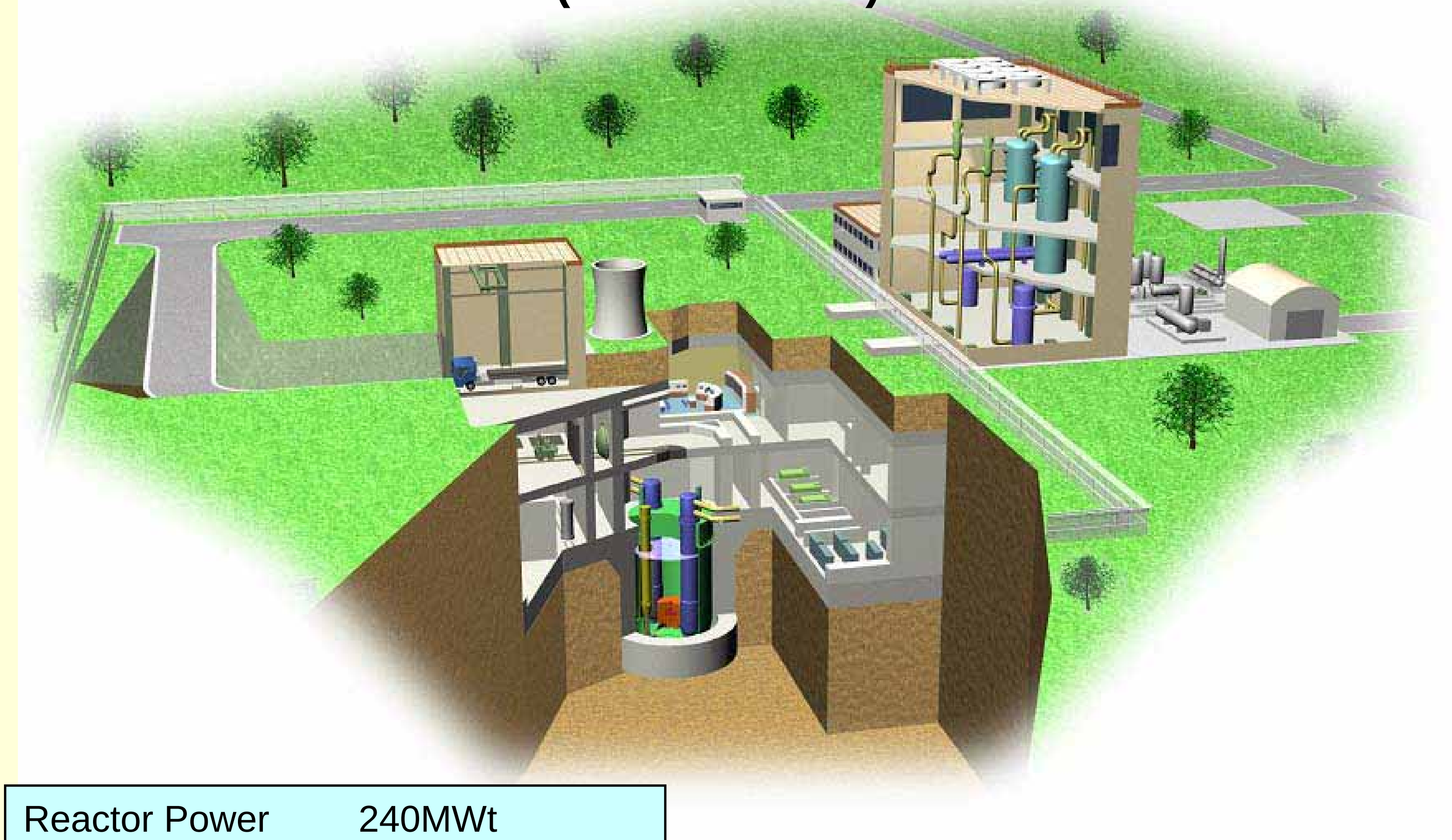
R=Nuclear Reactor

MR=Membrane Reformer

IHX=Intermediate Heat Exchanger

SG=Steam Generator

Bird-Eye View of Nuclear-Heated Natural Gas Membrane Reformer Hydrogen Production Plant using Sodium-Cooled Fast Reactor (MHI-ARTECH)



Reactor Power	240MWt
Core Outlet Temp	580C
H_2 Production	200,000 Nm^3/h
Natural Gas	50,000 Nm^3/h

Merits of Nuclear-Heated Recirculation-Type Membrane Reformer

- Supply of nuclear heat at medium reactor temperature (500~ 600C)
- Avoiding use of expensive heat-resistant materials and increased long-term durability
- No combustion of methane for the endothermic heat of reforming reaction, and consequently no combusted carbon dioxide emission
- Saving effect of natural gas, and consequently reduction of carbon dioxide emission, of more than 30% are expected when compared with conventional hydrogen production processes
- Separation of carbon dioxide for future sequestration requirements (Separation of CO_2 built into the process)

General Formulas of Reforming Reaction

Reaction formulas of steam reforming of hydrocarbons are generally expressed by the following equations;

$C_mH_n + mH_2O \rightarrow mCO + (m+n/2)H_2$ Reforming reaction

$mCO + mH_2O \rightarrow mCO_2 + mH_2$ Shift reaction

$C_mH_n + 2mH_2O \rightarrow mCO_2 + (2m+n/2)H_2$ Reforming-shift reaction

'Reforming' has generally meant the changing by heat treatment of a high-heating-value hydrocarbons into a gaseous mixture of lower heating value, approximating that commonly used in the local situation, with the resulting increase in volume. (Encyclopedia of Chemical Technology)

Moles of product hydrogen per unit C of hydrocarbon molecule

Fossil fuel	Substance	Representative Component's Molecular Formula	Mole of H_2 per C of C_mH_n
Natural gas	Methane	C_1H_4	4
Petroleum	LPG	C_4H_{10}	3.25
	Naphtha	C_6H_{14}	3.17
	Kerosene	$C_{12}H_{26}$	3.08
Coal	Coal	$C_1H_{0\sim1}$	2~2.5

Ratio of heat of reaction to heat of combustion of produced hydrogen in steam reforming reaction of representative fossil fuels / hydrocarbons

Fossil Fuel / Hydro-carbon	Representative Component's Molecular Formula	Steam Reforming Reaction Formula	Heat of Reaction / Mole of Hydrocarbon [kJ/mol-HC]	H_2 Heat of Combustion / Mole of Hydrocarbon [kJ/mol-HC]	Heat of Reaction / H_2 Heat of Combustion [%]
Natural Gas	C_1H_4	$CH_4+2H_2O \rightarrow CO_2+4H_2$	165.0	968	17.0
LPG	C_4H_{10}	$C_4H_{10}+8H_2O \rightarrow 4CO_2+13H_2$	486.6	3146	15.5
Naphtha	C_6H_{14}	$C_6H_{14}+12H_2O \rightarrow 6CO_2+19H_2$	739.3	4598	16.1
Kerosene	$C_{12}H_{26}$	$C_{12}H_{26}+24H_2O \rightarrow 12CO_2+37H_2$	1433.0	8954	16.0
Coal	C_1	$C+2H_2O \rightarrow CO_2+2H_2$	90	484	18.6

Synergy with Petroleum

Application of nuclear-heated membrane reformer

- Petroleum will probably keep its leading and exclusive share for transportation demand for the time being, especially in the OECD countries.
- With that background, it is considered important, from the standpoint of resource and environmental conservation, to produce hydrogen from petroleum for efficient energy utilization through fuel cells.

Advantage of Nuclear-Heating in the Steam Reforming
PETROLEUM PRODUCTS

- Conventional petroleum product combustion reformer
  - Petroleum is consumed for combustion and heat utilization efficiency is limited
  - About 70% efficiency in the reforming process
- Nuclear-heated membrane reformer
  - No petroleum is consumed for combustion and the yield of hydrogen is nearly stoichiometric
- Nuclear-heated SMR process will save more than 30% petroleum products consumption, comparing with the conventional SMR process.

Synergy with Coal
Application of nuclear-heated membrane reformer

- Coal has many advantages as a primary energy over other fossil fuels; abundant resource availability, superior supply stability and excellent cost competitiveness.

- When coal is liquefied or gasified to be a fluid fuel of liquid or gaseous hydrocarbon, then convenience of its energy utilization will increase.

- Further, if hydrogen is produced from coal and is utilized in fuel cells, then efficiency of its energy utilization will be increased.

Hydrogen Production via SNG* from Coal

** SNG = Synthetic or substitute natural gas (CH_4)*

Hydro-Gasification Reaction of Coal;

(The ARCH Process under Development)

$C + 2H_2 = CH_4$ + 75 kJ/mol

Steam Reforming-Shift Reaction of Methane;

$CH_4 + 2H_2O = CO_2 + 4H_2$ -165 kJ/mol

- *Hydro-gasification process (high temperature and pressure) to be conducted outside of nuclear systems*
- *Reforming-shift reaction process to be conducted by the nuclear-heated recirculation-type membrane reformer*

Advantage of Nuclear-Heating in the Steam Reforming
COAL

- Conventional steam-coal gasification
  - 65~70% conversion efficiency (Texaco Process)
- Combined ARCH and Membrane Reformer Process
  - 60% of coal converted to SNG and then hydrogen (about 70% conversion efficiency)
  - 40% of coal discharged as char (carbon and ash)
  - No combustion of coal for supplying heat, thus reducing carbon dioxide emission

Wrap-up

- The membrane reformer process using natural gas and sodium cooled reactor can compete economically with conventional hydrogen production methods.
- The foremost feature of this process is to reduce the consumption of fossil fuels, and consequently emission of carbon dioxide, by 30% or more, compared with conventional hydrogen production processes.
- Application of nuclear-heated membrane reformer to petroleum and coal is considered possible with a similar saving effect as for natural gas.
- Use of fast reactors for the heating can save the fissile uranium resources which would become critical in the 21st century when nuclear energy is used for hydrogen production in addition to electricity generation.

Synergy of Fossil and Nuclear

1+1=3

- Most discussions of future global energy supply anticipate continued use of fossil fuels to some extent for a century or so while reducing carbon dioxide emission. The synergistic production of hydrogen using both energy sources could enable nuclear energy to improve the efficiency with which valuable fossil fuel resources are consumed.
- With all these benefits, the synergistic blending of fossil fuels and nuclear energy to produce hydrogen can be an effective solution for the world until competitive thermo-chemical water splitting processes are available.