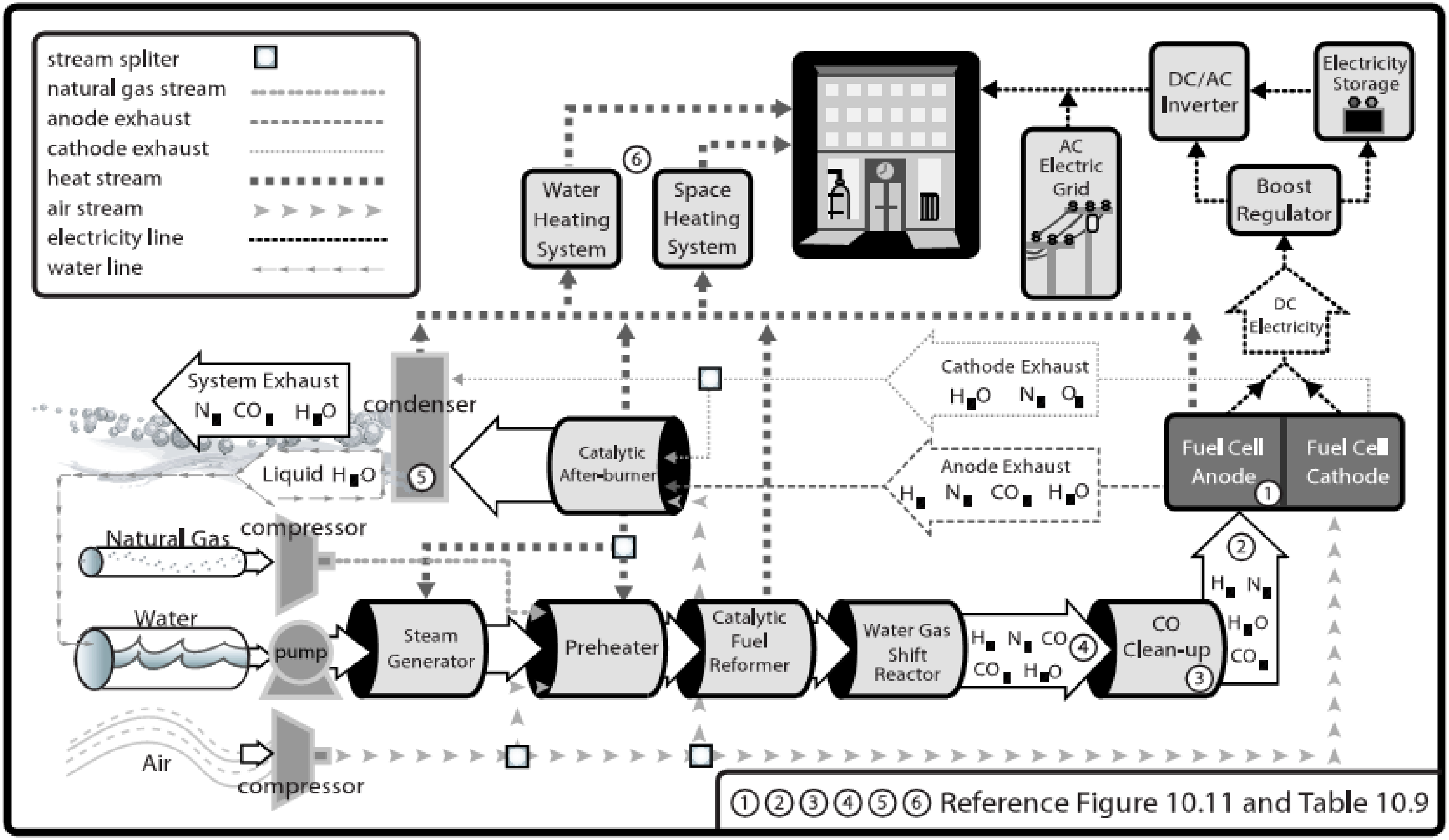
Fuel Cell System Integration & Sub-System Design

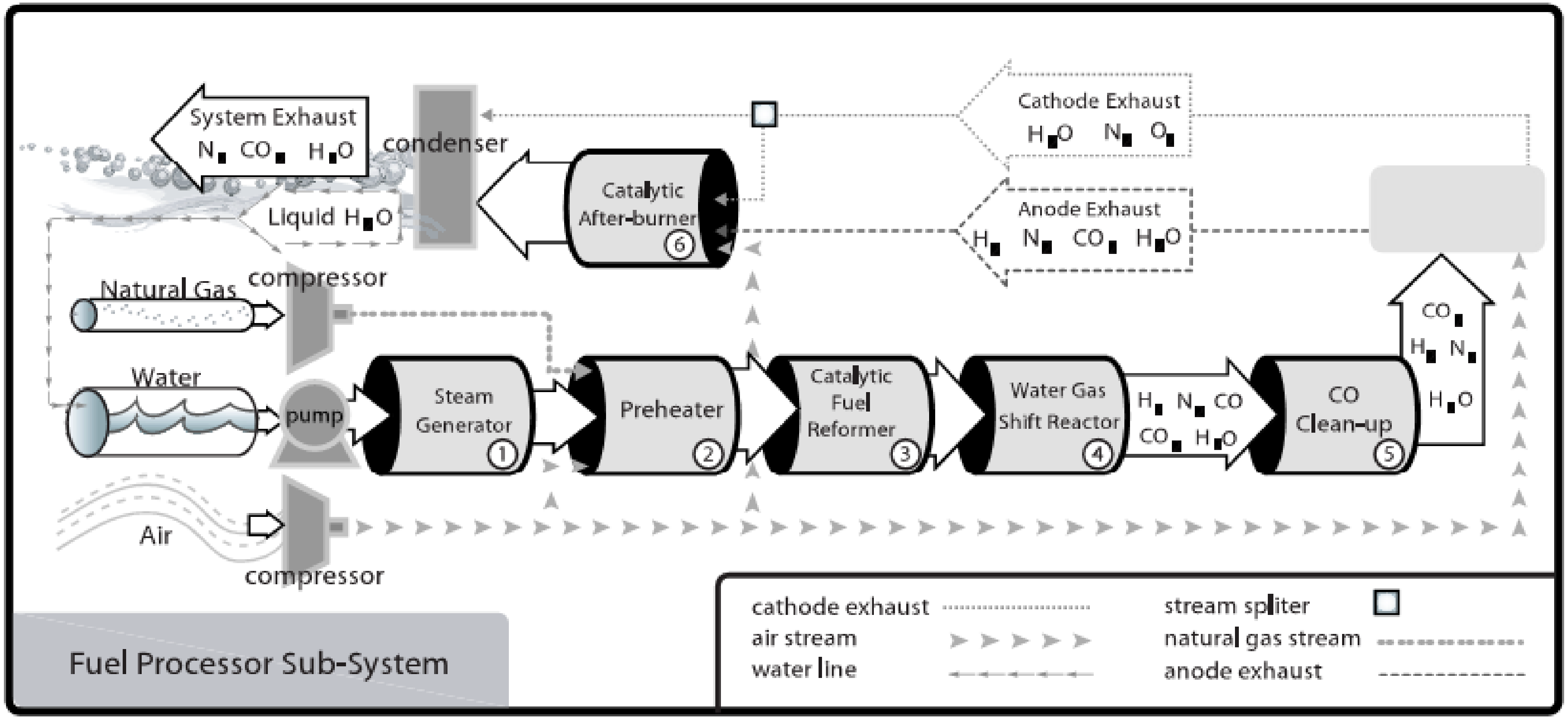
CHP Fuel Cell Systems

- Fuel processing sub-systems
- Fuel cell sub-systems
- Thermal management
- Power electronic sub-systems

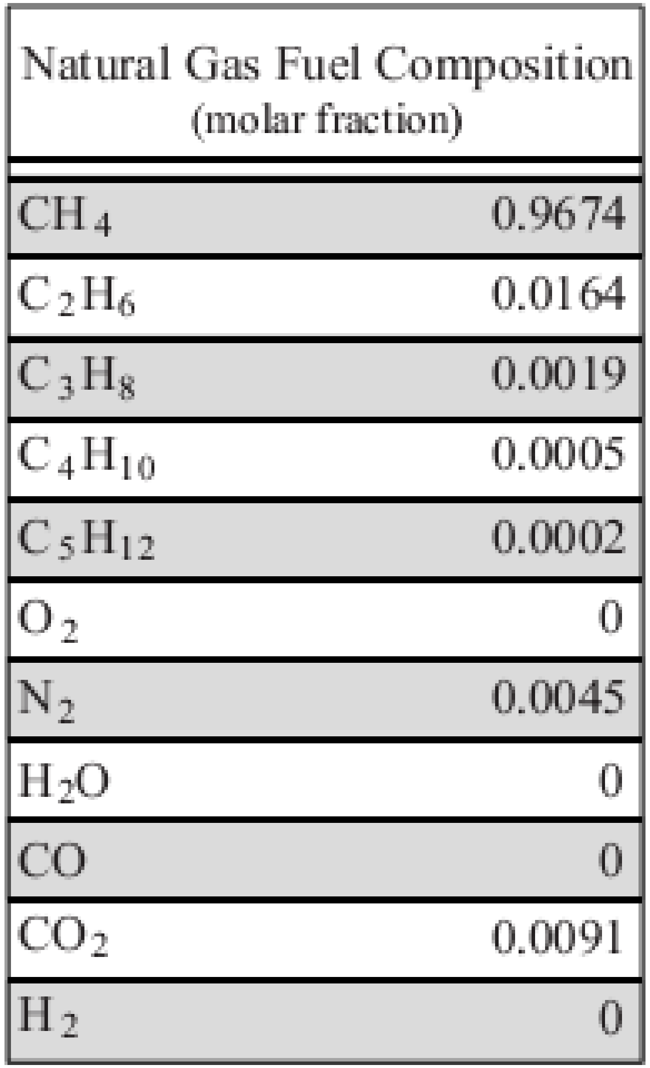
CHP Fuel Cell Systems



Fuel Processor Sub System

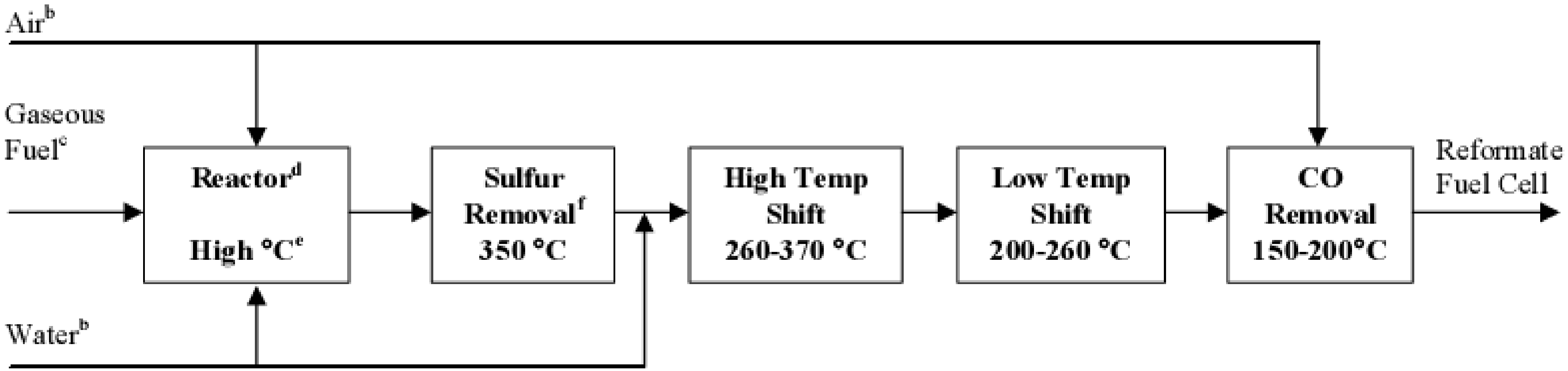


Fuel Processor Sub System



Natural Gas Fuel Composition (molar fraction)	
CH_4	0.9674
C_2H_6	0.0164
C_3H_8	0.0019
C_4H_{10}	0.0005
C_5H_{12}	0.0002
O_2	0
N_2	0.0045
H_2O	0
CO	0
CO_2	0.0091
H_2	0

Fuel Processor Sub System



Air[b]

Gaseous Fuel[c]

Reactor[d]

High °C[e]

Sulfur Removal[f]

350 °C

High Temp Shift

260-370 °C

Low Temp Shift

200-260 °C

CO Removal

150-200°C

Reformate to Fuel Cell

Water[b]

a) - For MCFC & SOFC, no high temperature shift, low temperature shift, or CO removal required.
   - For PAFC and circulating AFC, no CO removal required after low temperature shift.
   - For PEFC, all components required except that for high temperature CO removal eliminated or reduced in complexity.

b) Possible to use residual air, water, and heat of fuel effluent from fuel cell and other downstream components.

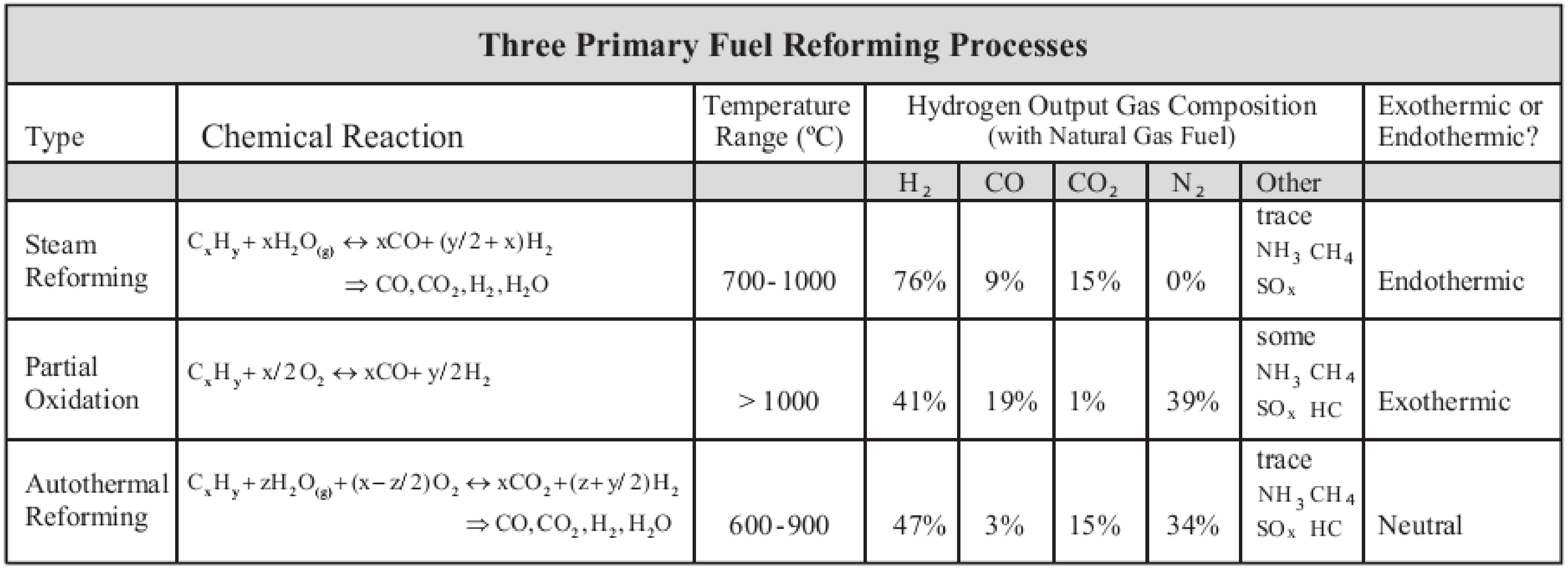
c) Vaporizer required for liquid fuels.

d) Non-catalytic POX fuel processor does not require water.

e) Temperature dependent on fuel, sulfur content of fuel, and type of reactor.

f) Can be located prior to, within, or after the reactor; liquid desulfurizer located prior to the vaporizer.

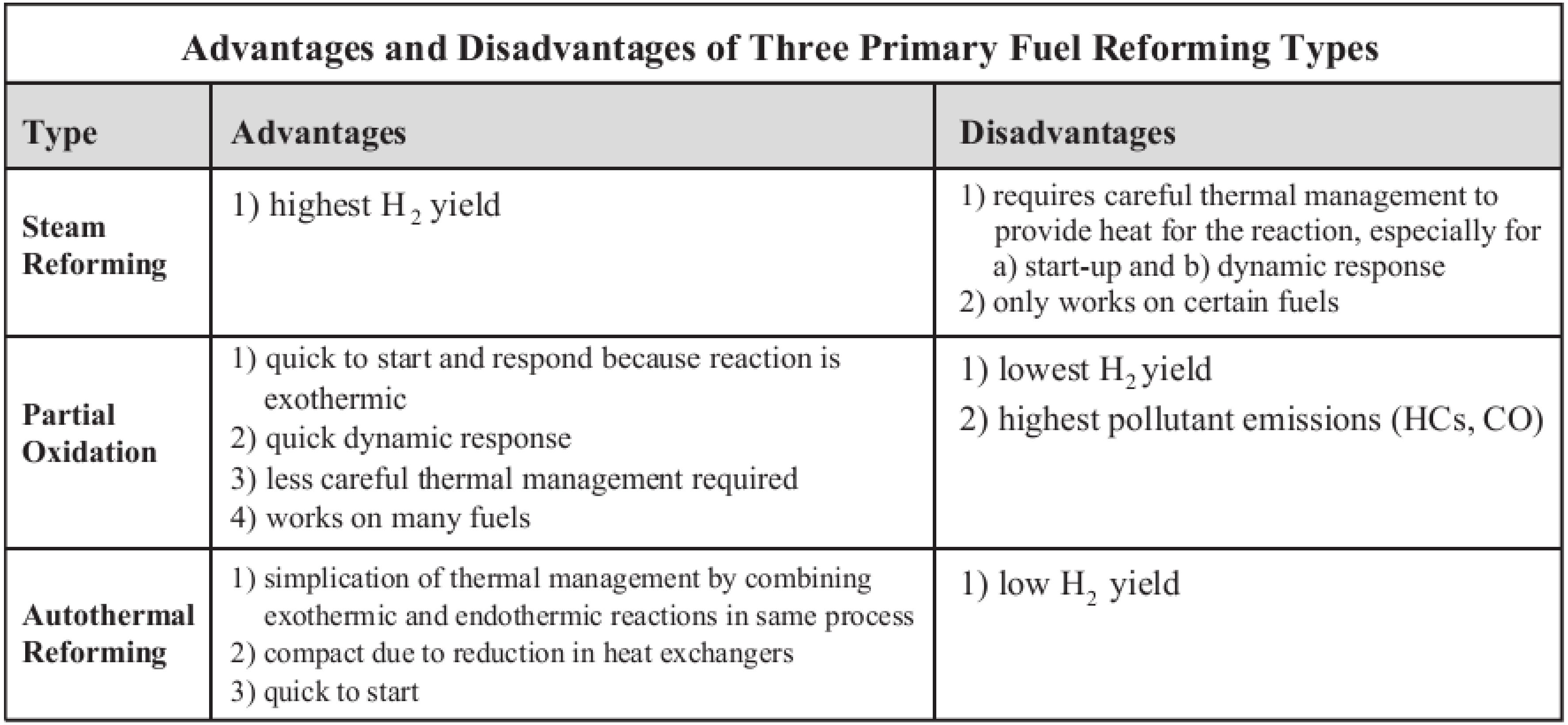
External Reforming



Three Primary Fuel Reforming Processes

Type	Chemical Reaction	Temperature Range (ºC)	Hydrogen Output Gas Composition (with Natural Gas Fuel)					Exothermic or Endothermic?
			H_2	CO	CO_2	N_2	Other	
Steam Reforming	$C_xH_y + xH_2O_{(g)} \leftrightarrow xCO + (y/2 + x)H_2$ $\Rightarrow CO, CO_2, H_2, H_2O$	700-1000	76%	9%	15%	0%	trace NH_3 CH_4 SO_x	Endothermic
Partial Oxidation	$C_xH_y + x/2\,O_2 \leftrightarrow xCO + y/2\,H_2$	> 1000	41%	19%	1%	39%	some NH_3 CH_4 SO_x HC	Exothermic
Autothermal Reforming	$C_xH_y + zH_2O_{(g)} + (x - z/2)O_2 \leftrightarrow xCO_2 + (z + y/2)H_2$ $\Rightarrow CO, CO_2, H_2, H_2O$	600-900	47%	3%	15%	34%	trace NH_3 CH_4 SO_x HC	Neutral

External Reforming



Advantages and Disadvantages of Three Primary Fuel Reforming Types

Type	Advantages	Disadvantages
Steam Reforming	1) highest H_2 yield	1) requires careful thermal management to provide heat for the reaction, especially for a) start-up and b) dynamic response 2) only works on certain fuels
Partial Oxidation	1) quick to start and respond because reaction is exothermic 2) quick dynamic response 3) less careful thermal management required 4) works on many fuels	1) lowest H_2 yield 2) highest pollutant emissions (HCs, CO)
Autothermal Reforming	1) simplication of thermal management by combining exothermic and endothermic reactions in same process 2) compact due to reduction in heat exchangers 3) quick to start	1) low H_2 yield

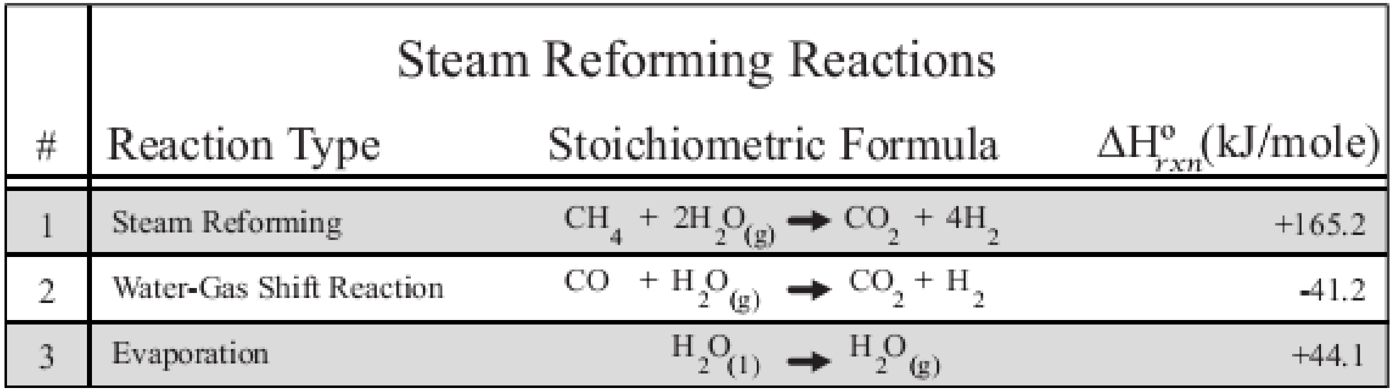
Steam Reforming

$$C_xH_y + xH_2O_{(g)} \leftrightarrow xCO + (y/2 + x)H_2 \Rightarrow CO, CO_2, H_2, H_2O$$

(endothermic)

$$\downarrow$$

$$CO + H_2O_{(g)} \leftrightarrow CO_2 + H_2$$ (WGS with excess water)



Steam Reforming Reactions

#	Reaction Type	Stoichiometric Formula	ΔH^{o}_{rxn}(kJ/mole)
1	Steam Reforming	$CH_4 + 2H_2O_{(g)} \rightarrow CO_2 + 4H_2$	+165.2
2	Water-Gas Shift Reaction	$CO + H_2O_{(g)} \rightarrow CO_2 + H_2$	-41.2
3	Evaporation	$H_2O_{(1)} \rightarrow H_2O_{(g)}$	+44.1

Partial Oxidation

- Complete oxidation (oxygen rich)

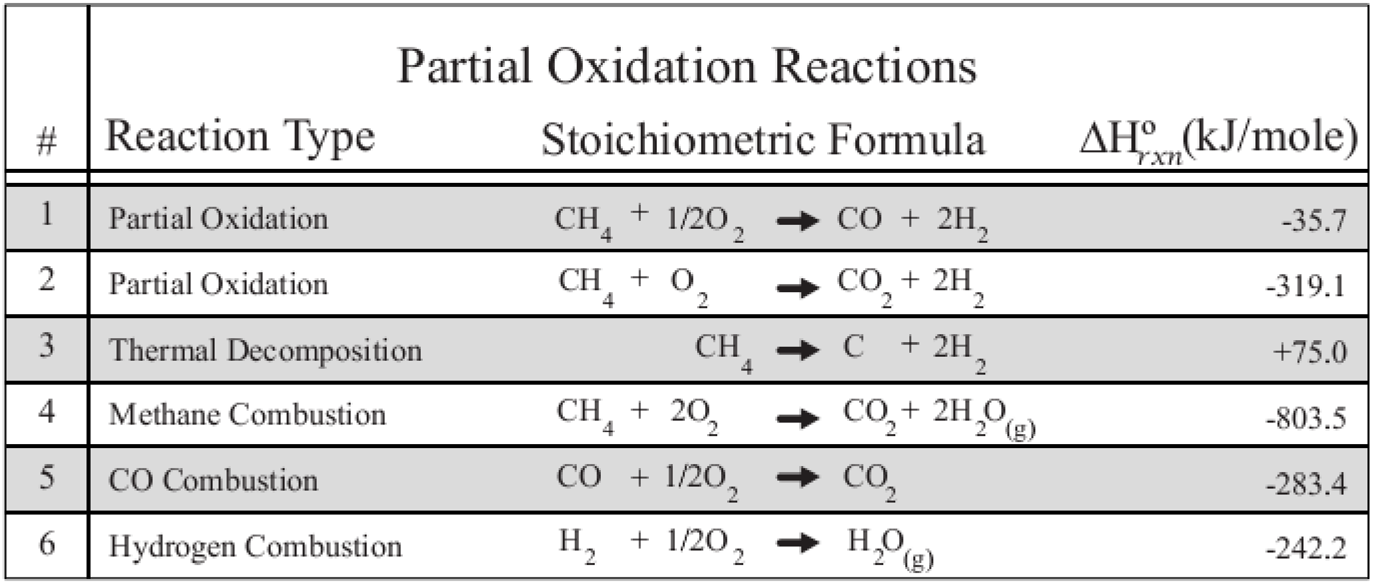
$C_3H_8 + xO_2 \leftrightarrow yCO_2 + zH_2O$ (exothermic)

- Partial oxidation (fuel rich)

$C_xH_y + \frac{x}{2}O_2 \leftrightarrow xCO + \frac{y}{2}H_2$ (exothermic)

↓

$CO + H_2O_{(g)} \leftrightarrow CO_2 + H_2$ (WGS with excess water)



Partial Oxidation Reactions

#	Reaction Type	Stoichiometric Formula	ΔH^o_{rxn}(kJ/mole)
1	Partial Oxidation	$CH_4 + 1/2O_2 \rightarrow CO + 2H_2$	-35.7
2	Partial Oxidation	$CH_4 + O_2 \rightarrow CO_2 + 2H_2$	-319.1
3	Thermal Decomposition	$CH_4 \rightarrow C + 2H_2$	+75.0
4	Methane Combustion	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O_{(g)}$	-803.5
5	CO Combustion	$CO + 1/2O_2 \rightarrow CO_2$	-283.4
6	Hydrogen Combustion	$H_2 + 1/2O_2 \rightarrow H_2O_{(g)}$	-242.2

Autothermal Reforming

$$C_xH_y + zH_2O_{(l)} + (x - z/2)O_2 \leftrightarrow xCO_2 + (z + y/2)H_2$$
$$\Rightarrow CO, CO_2, H_2, H_2O$$

- Neutral reaction by proper steam to carbon ratio (z/x)

Water Gas Shift Reactors

$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta \hat{h}_r(25°C) = -42.1\ kJ/mol$

(exothermic)

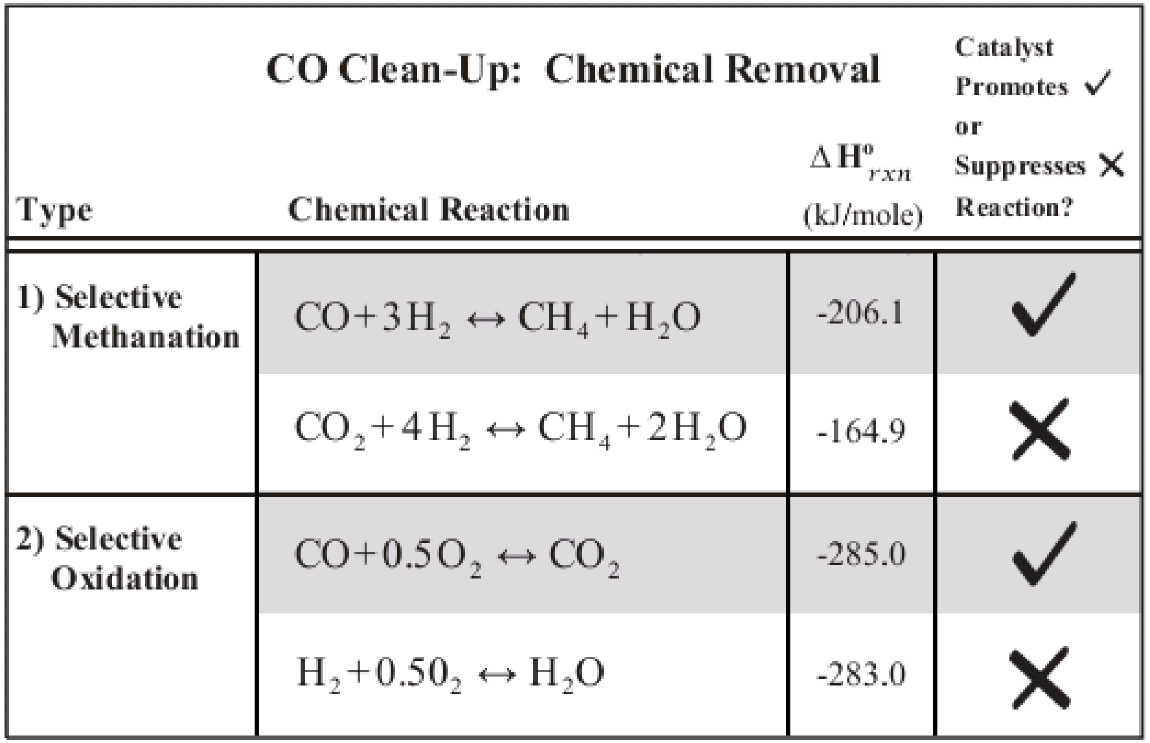
- High T
  - Equilibrium shift to the reactant side
  - Fast kinetics
- Low T
  - Equilibrium shift to the product side
  - Slow kinetics

* 1st stage: High T => 2nd stage: Low T

Carbon Monoxide Clean-up

- Chemical reaction
  - Selective methanation of CO
  - Selective oxidation of CO
- Physical seperation
  - Pressure-swing absorption
  - Membrane seperation

Chemical Reaction

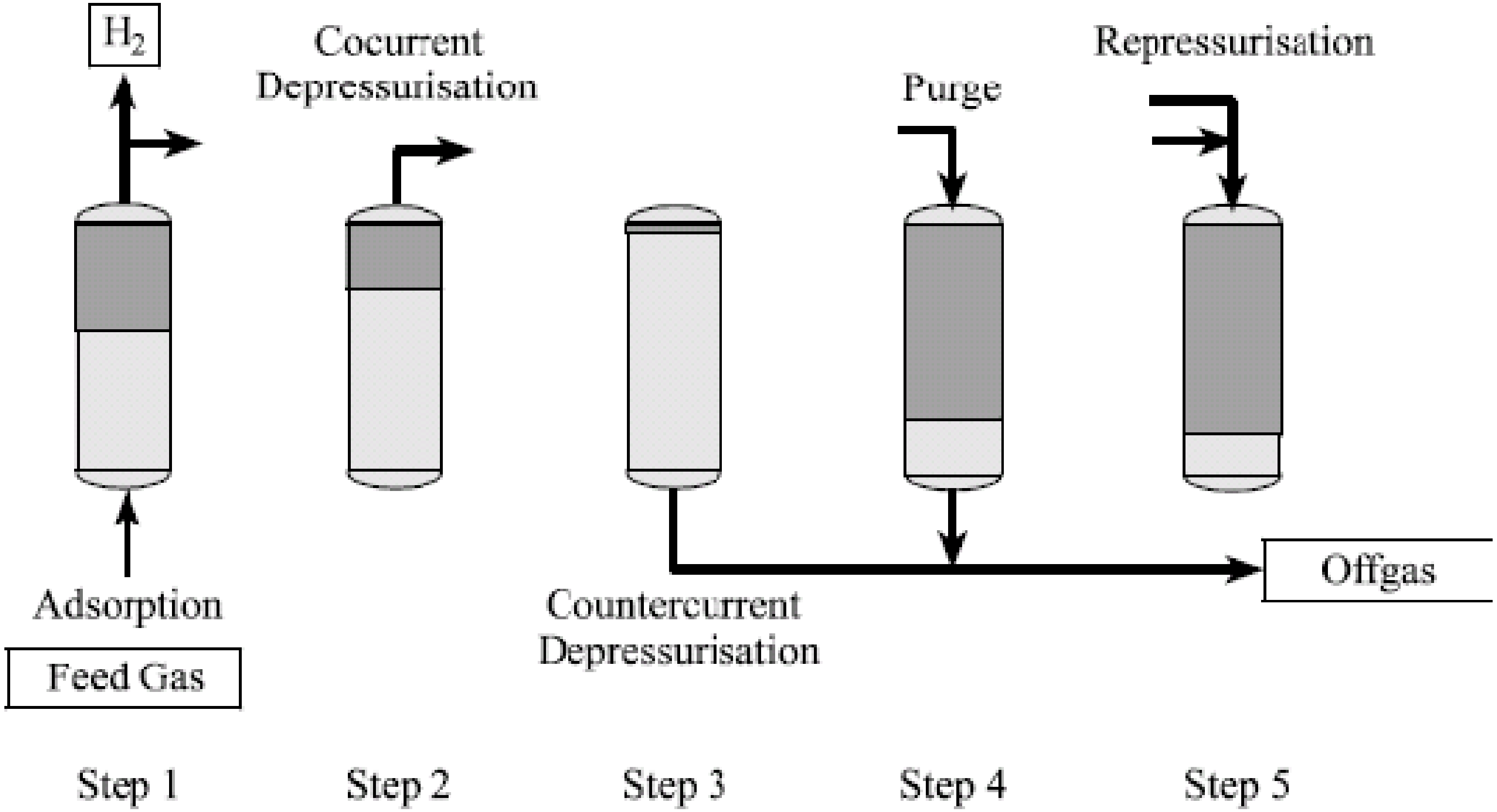


CO Clean-Up: Chemical Removal

Type	Chemical Reaction	ΔH^o_{rxn} (kJ/mole)	Catalyst Promotes ✓ or Suppresses ✗ Reaction?
1) Selective Methanation	$CO+3H_2 \leftrightarrow CH_4+H_2O$	-206.1	✓
	$CO_2+4H_2 \leftrightarrow CH_4+2H_2O$	-164.9	✗
2) Selective Oxidation	$CO+0.5O_2 \leftrightarrow CO_2$	-285.0	✓
	$H_2+0.50_2 \leftrightarrow H_2O$	-283.0	✗

- Low T preferred for selective
- Multi-stage catalyst bed in decreasing temperature

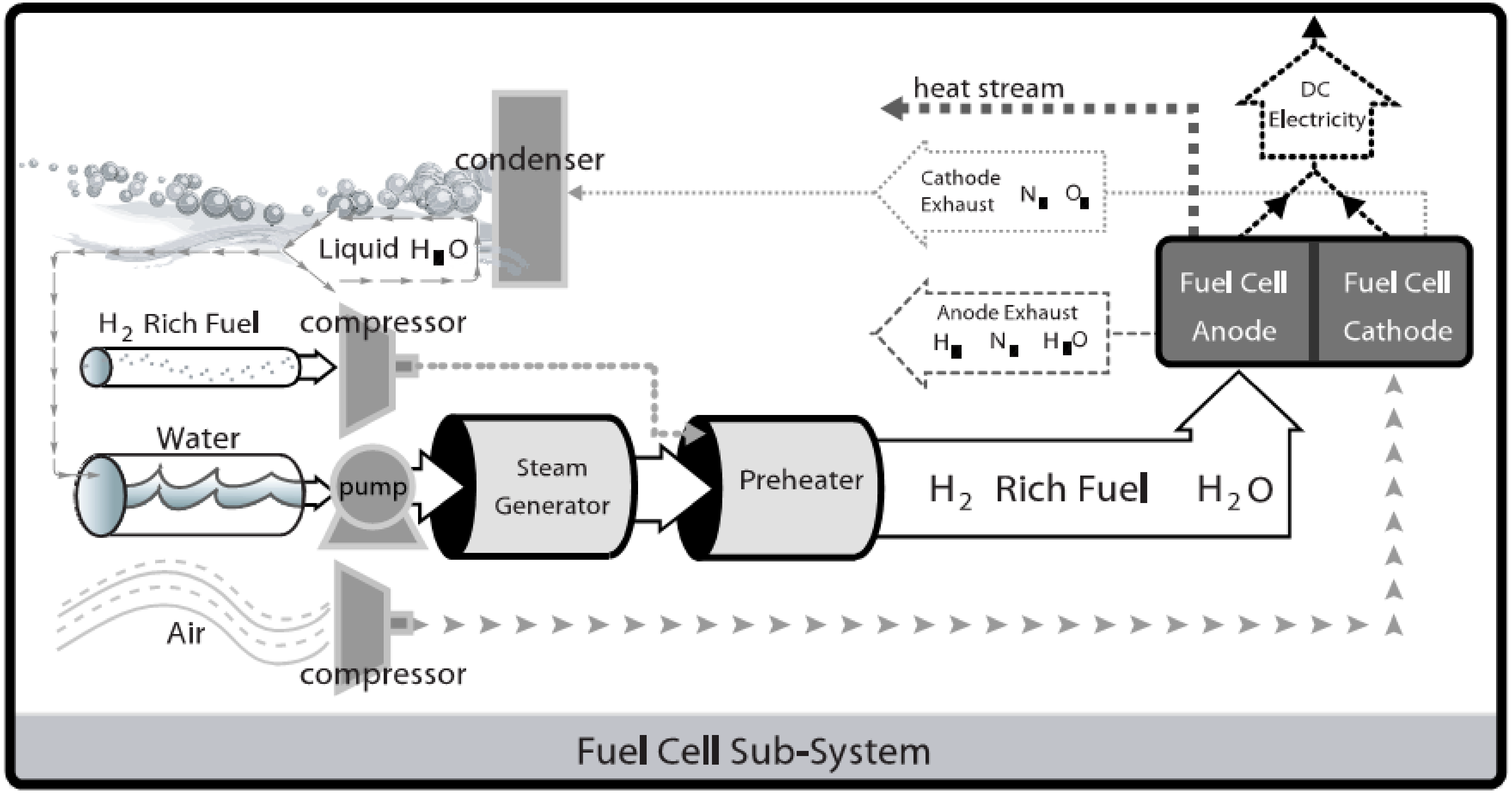
Pressure Swing Absorption



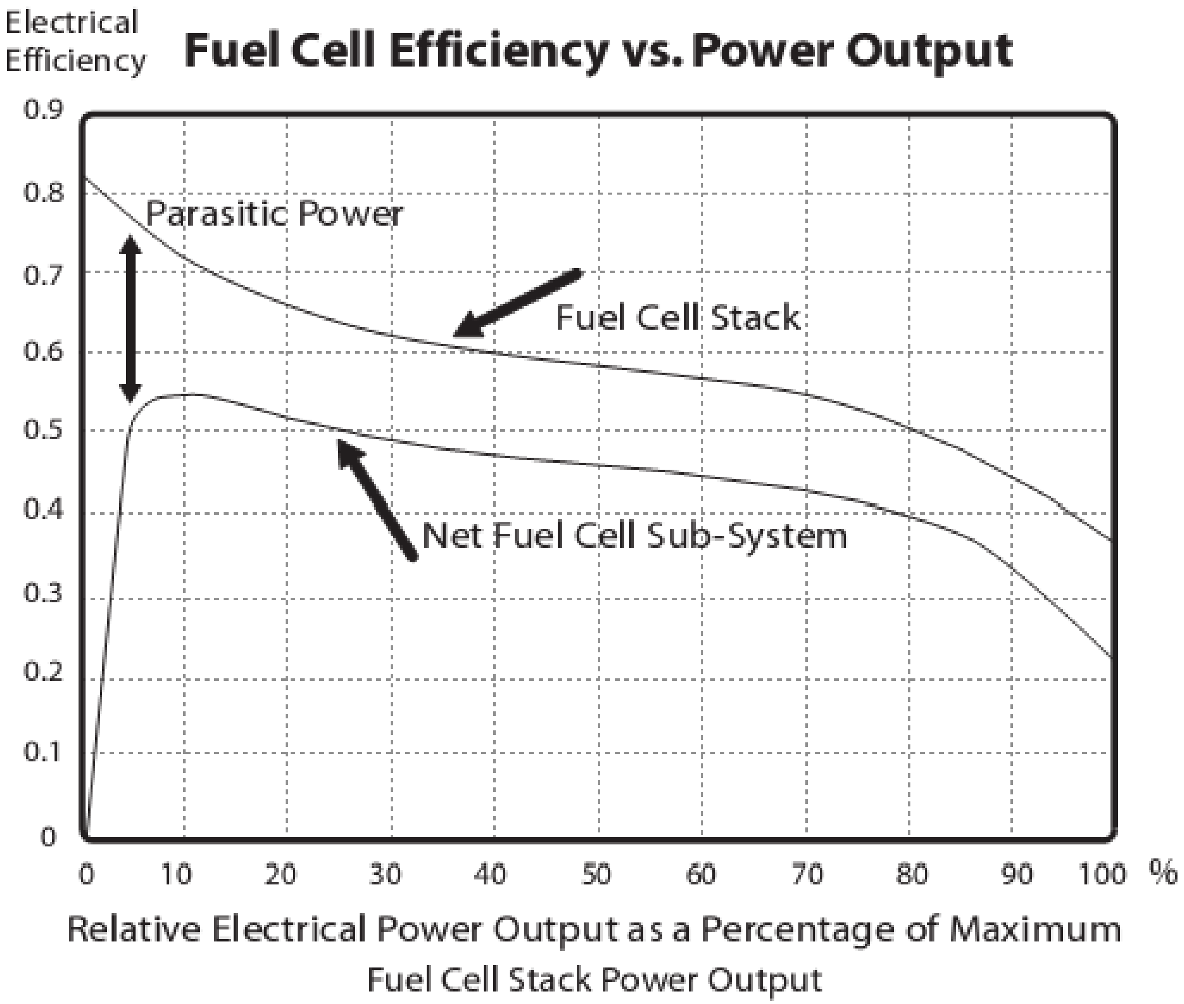
Membrane Separation

- Palladium
  - Pressure difference
  - Temperature
  - Thickness
- Purging
  - Removes other gas near surface
- Pinhole leaks

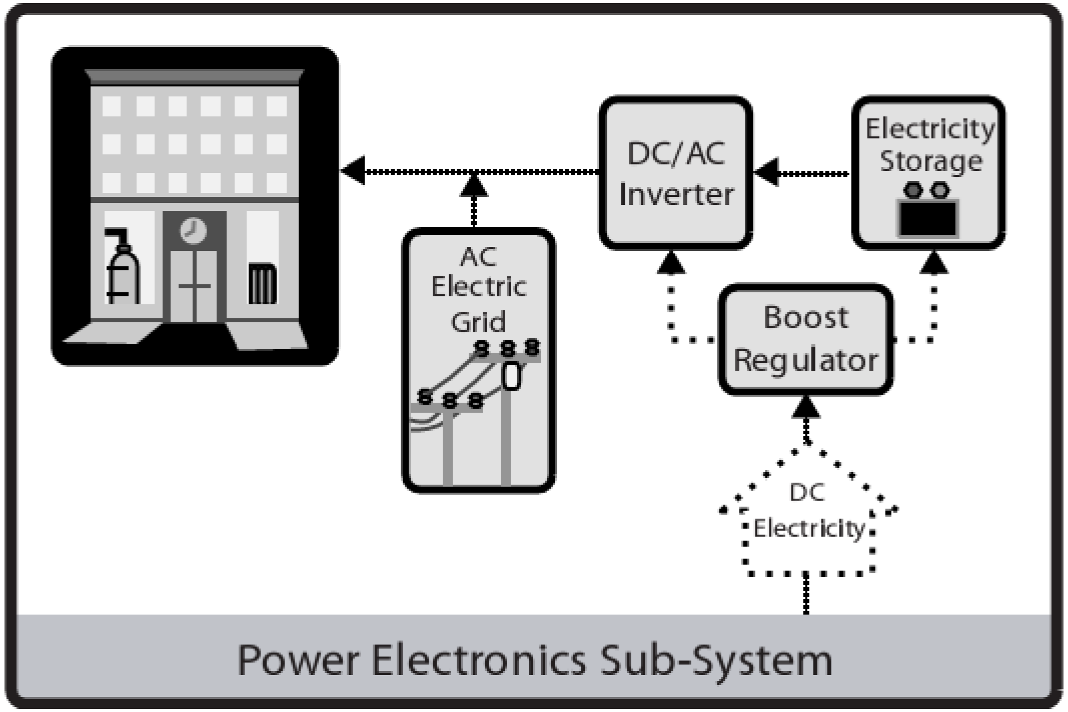
Fuel Cell Systems



Fuel Cell Systems

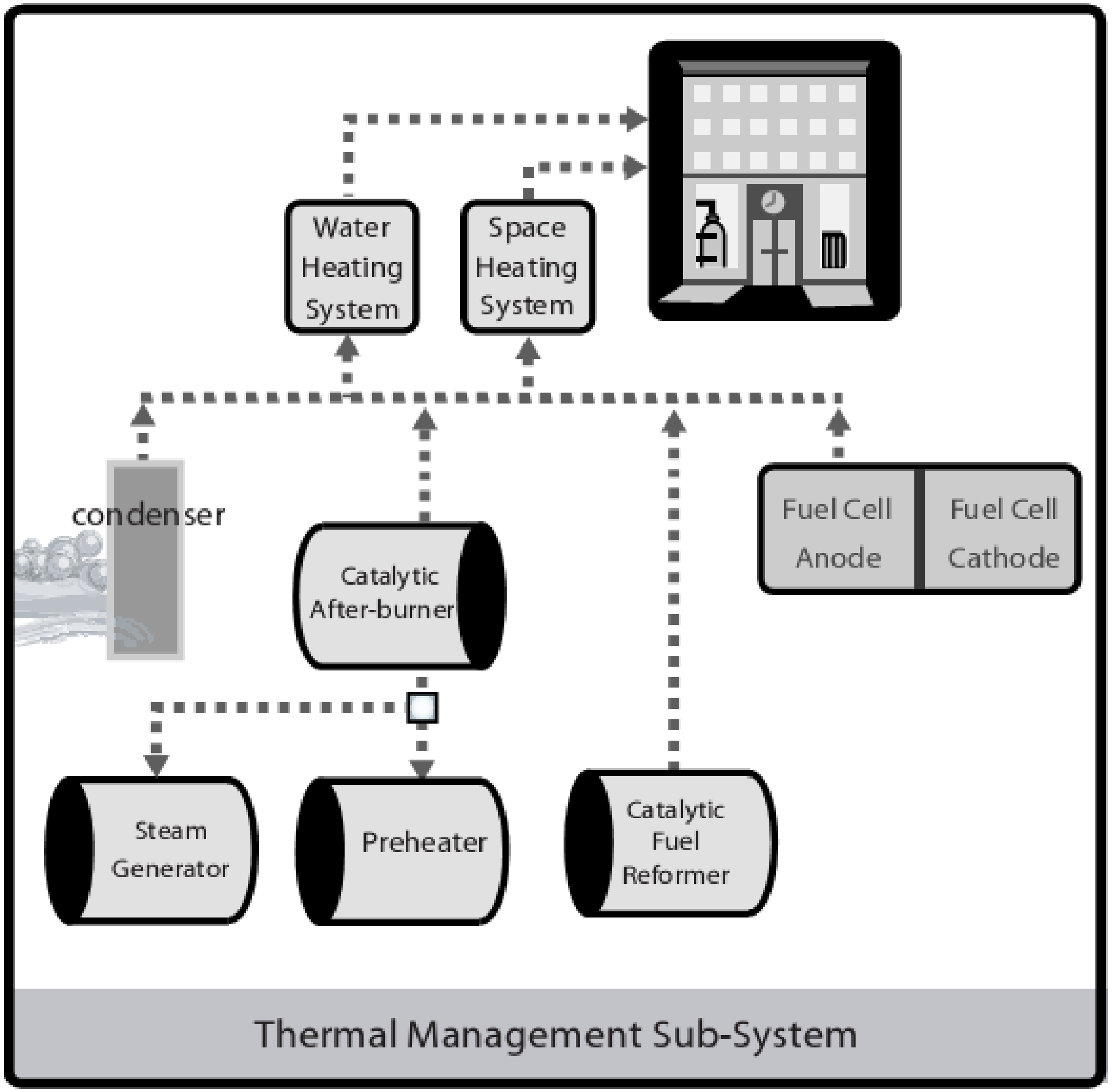


Power Electronics Sub-Systems

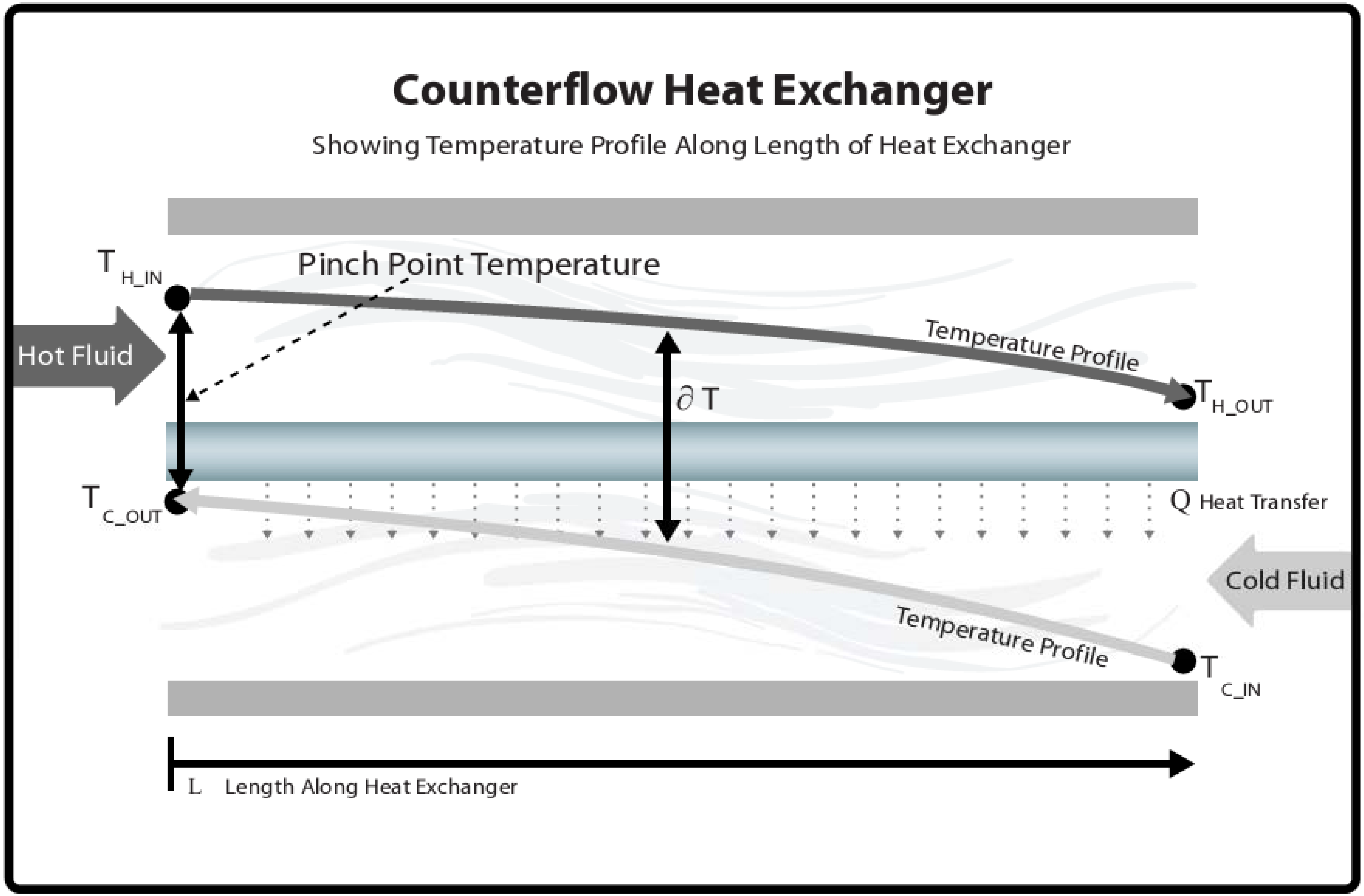


- Power conditioning
- Supply management

Thermal Management Sub-Systems



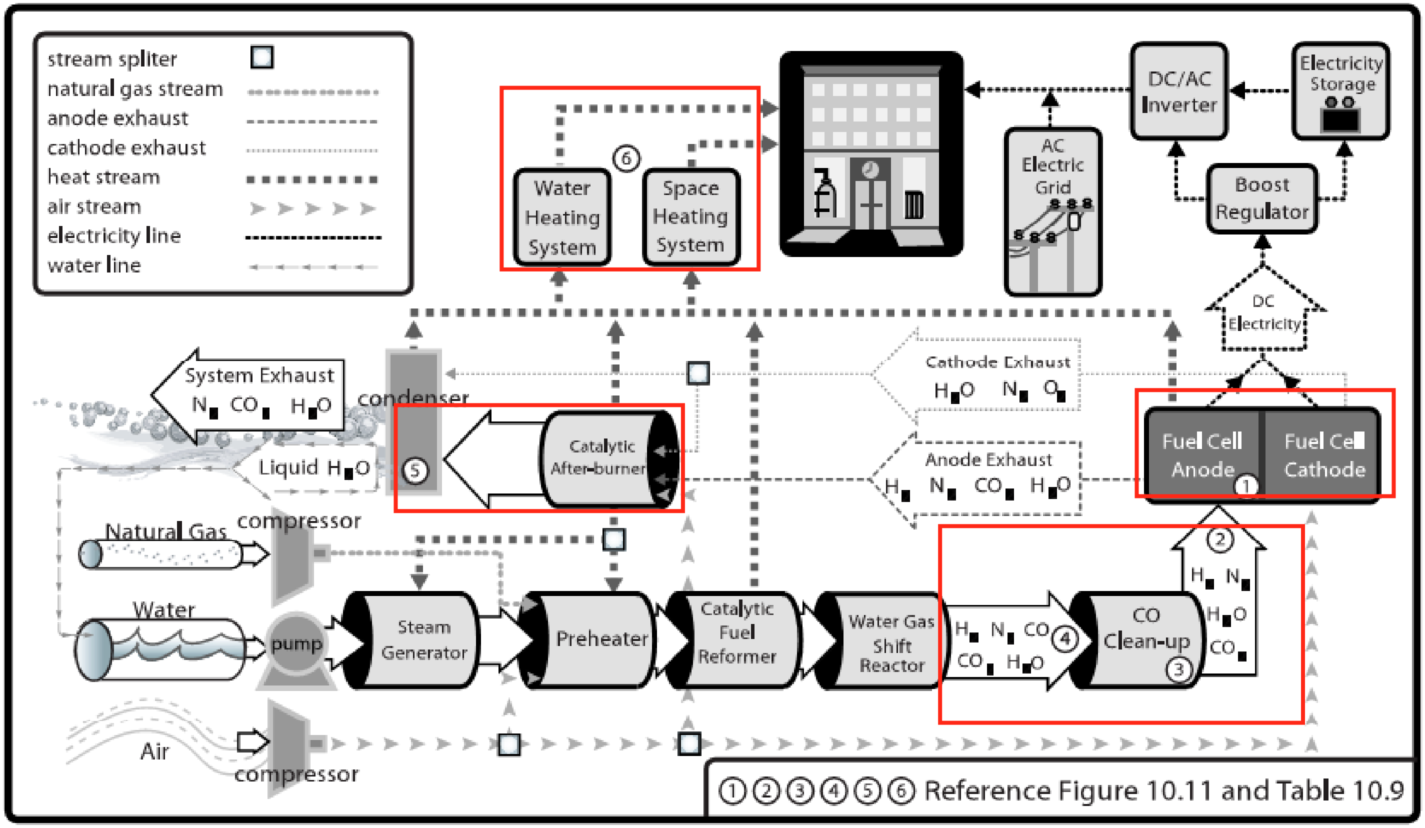
Heat Exchanger



Pinch Point Analysis

1. Identify hot and cold streams in the system
2. Determine thermal data for these streams.
3. Select a minimum acceptable temperature difference ($dT_{min,set}$) between hot and cold streams
4. Construct temperature vs. enthalpy diagrams and check $dT_{min} > dT_{min,set}$
5. If $dT_{min} < dT_{min,set}$, change heat exchanger orientation.
6. Conduct scenario analysis of heat exchanger orientation until $dT_{min} > dT_{min,set}$

Stream Identification



1. the hot reformate stream exiting the water gas shift reactor and eventually entering the fuel cell's anode (labeled No. 4 through to 2);
2. the cooling loop for the fuel cell stack (labeled No. 1), and
3. the hot anode and cathode exhaust stream exiting the afterburner and entering the condenser (labeled No. 5).

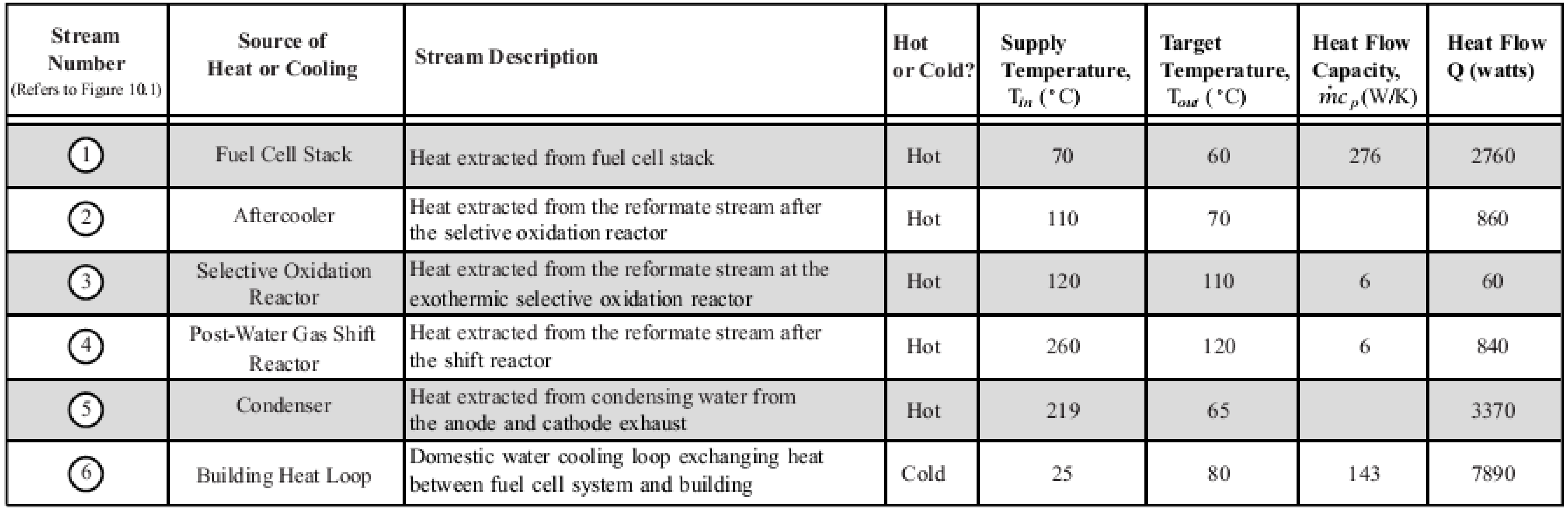
Thermal Data Determination

a) The supply temperature (T_{in}), the initial temperature at which the stream is available before entering a heat exchanger;

b) The target temperature (T_{out}), the desired outlet temperature for the stream upon exiting a heat exchanger;

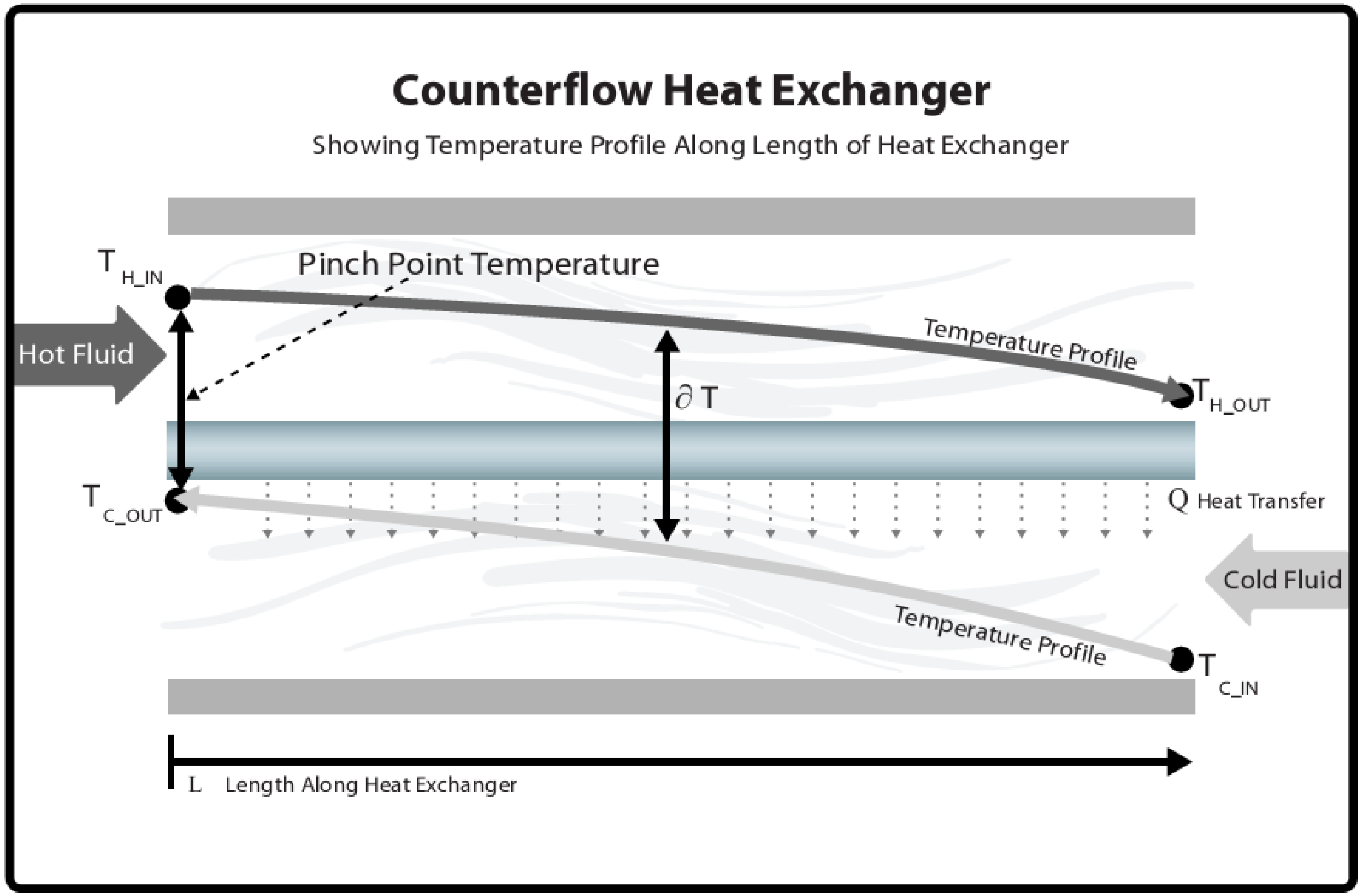
c) The heat capacity flow rate ($\dot{m}c_p$), the product of the stream's mass flow rate ($\dot{m}$) in kg/sec and the specific heat of the fluid in the stream (c_p) in $kJ/kg°C$, whereby the specific heat of the stream is assumed constant over the temperature range;

d) The change in enthalpy (dH) in the stream passing through the heat exchanger.



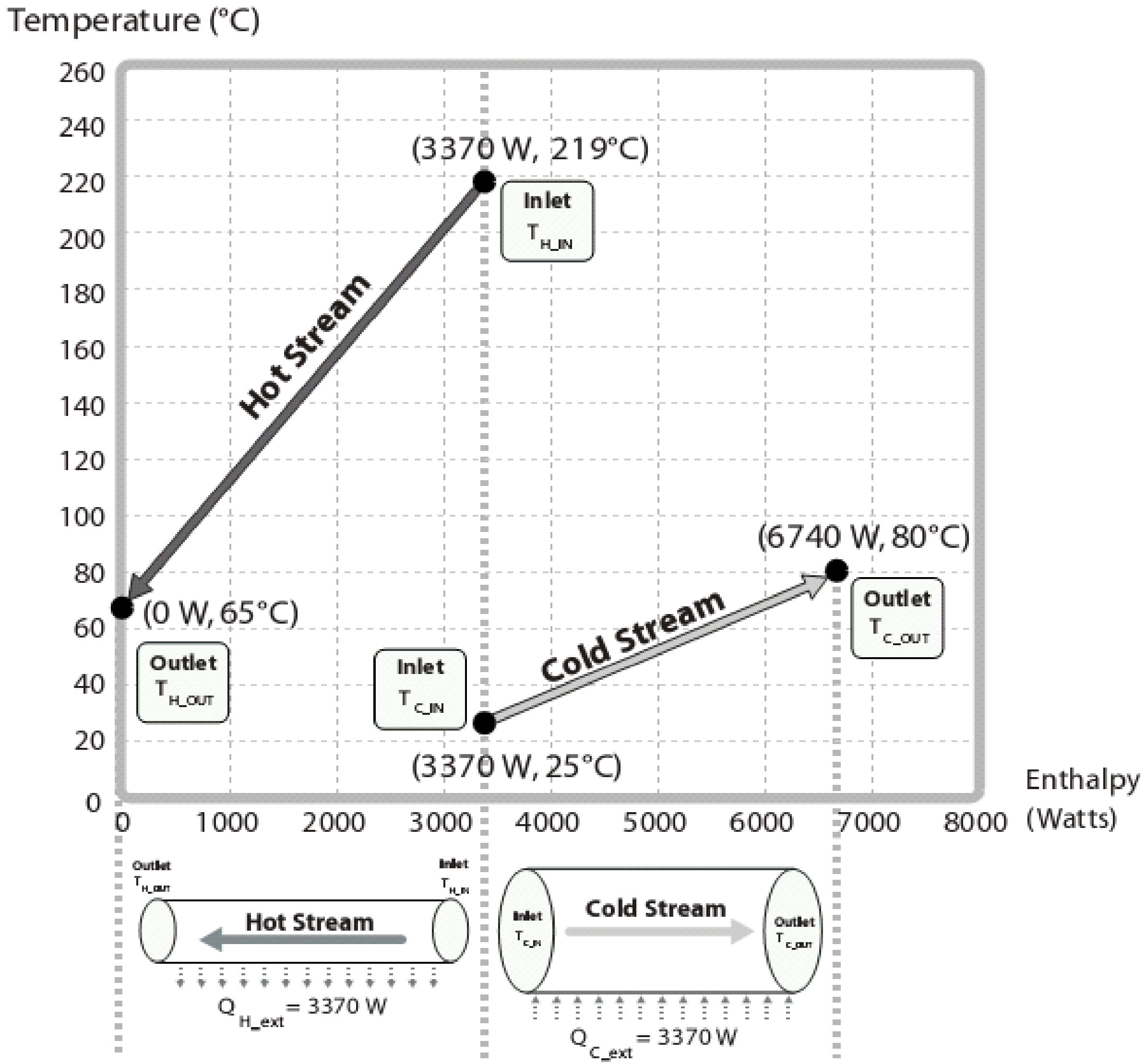
Stream Number (Refers to Figure 10.1)	**Source of Heat or Cooling**	**Stream Description**	**Hot or Cold?**	**Supply Temperature,** T_{in} (°C)	**Target Temperature,** T_{out} (°C)	**Heat Flow Capacity,** $\dot{m}c_p$(W/K)	**Heat Flow Q (watts)**
①	Fuel Cell Stack	Heat extracted from fuel cell stack	Hot	70	60	276	2760
②	Aftercooler	Heat extracted from the reformate stream after the seletive oxidation reactor	Hot	110	70		860
③	Selective Oxidation Reactor	Heat extracted from the reformate stream at the exothermic selective oxidation reactor	Hot	120	110	6	60
④	Post-Water Gas Shift Reactor	Heat extracted from the reformate stream after the shift reactor	Hot	260	120	6	840
⑤	Condenser	Heat extracted from condensing water from the anode and cathode exhaust	Hot	219	65		3370
⑥	Building Heat Loop	Domestic water cooling loop exchanging heat between fuel cell system and building	Cold	25	80	143	7890

Selection of $dT_{min.set}$



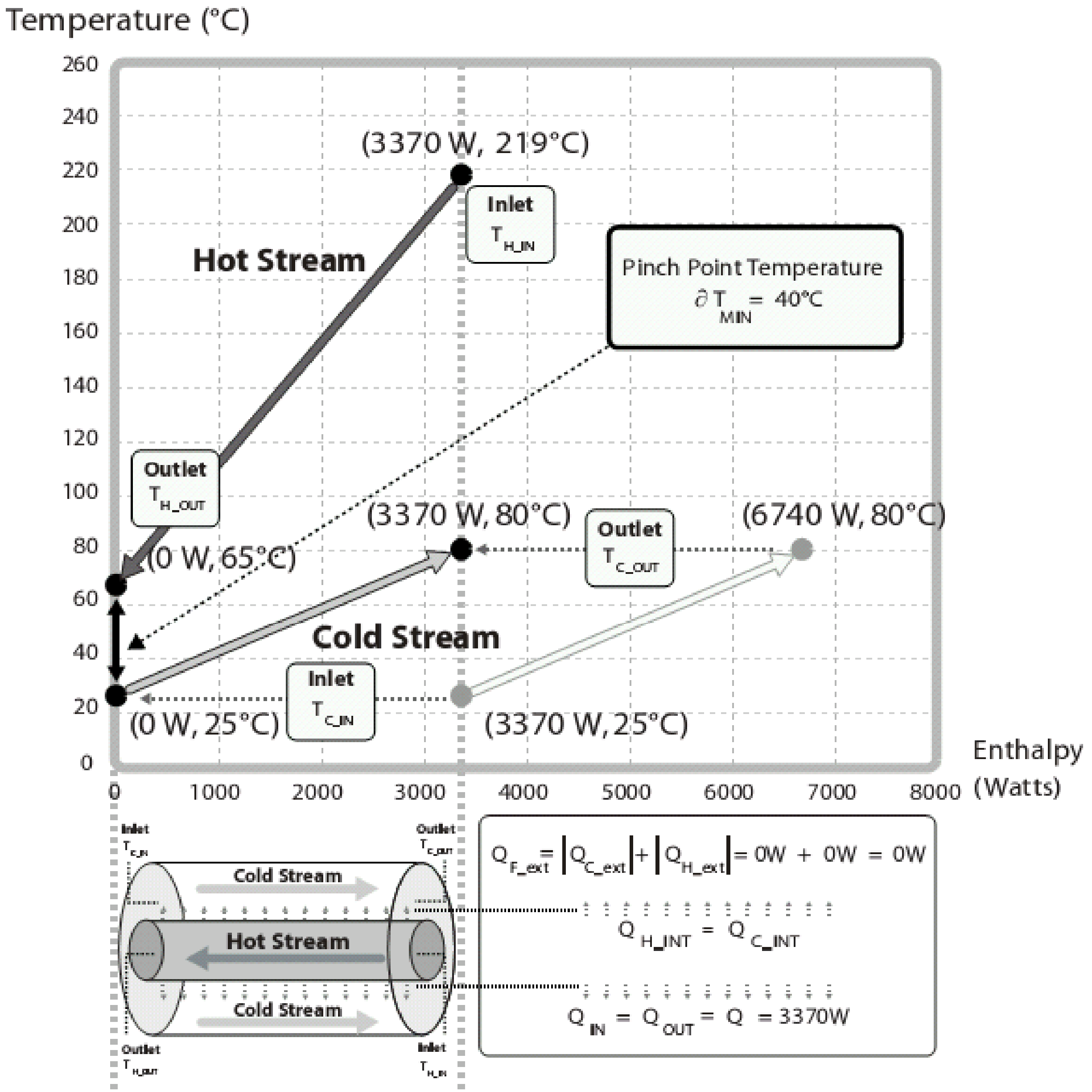
- Minimun dT at L=0
- dT = 3~40C

T-H Diagram: $dT_{min} > dT_{min,set}$

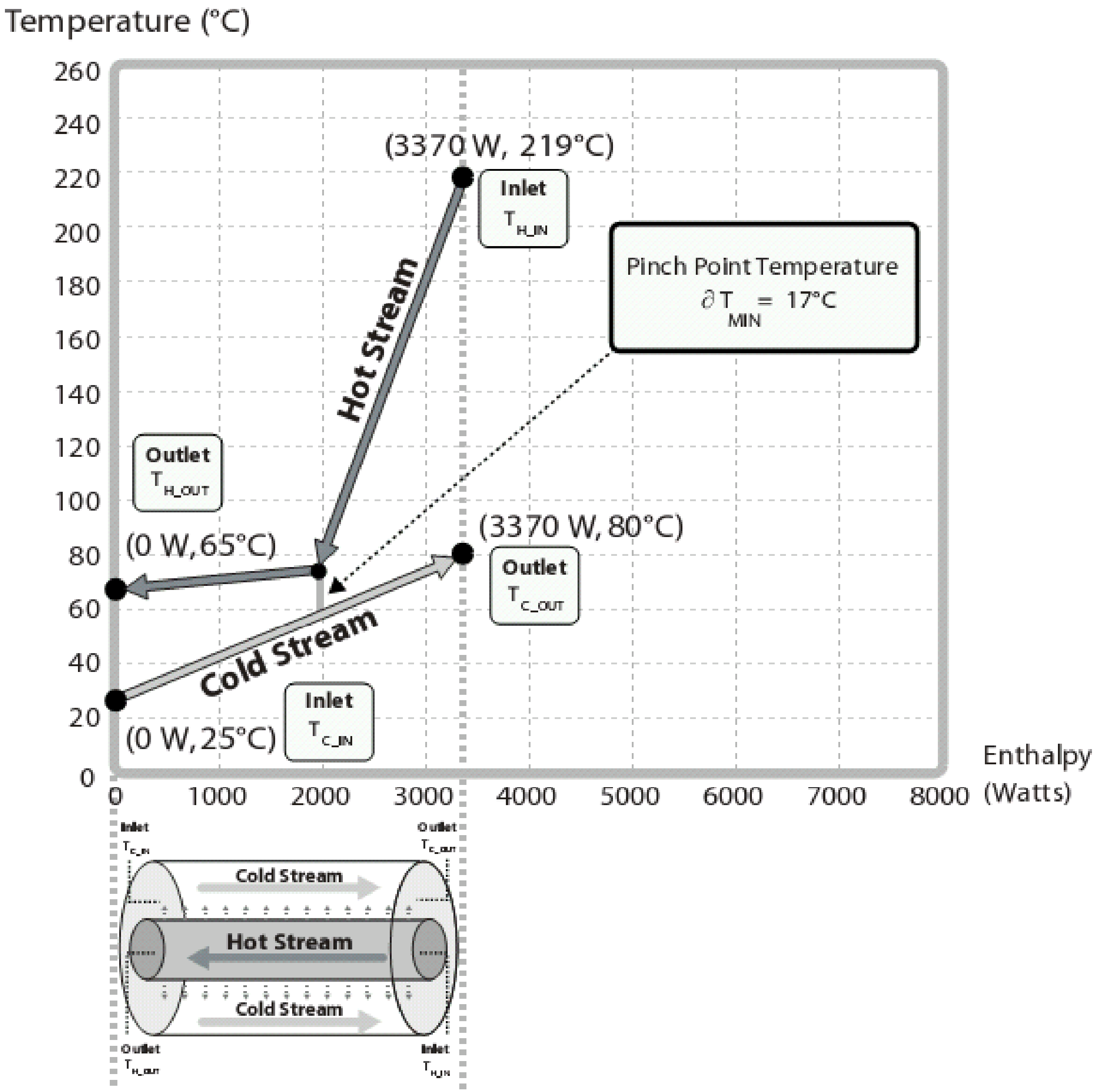


$$Q_{F\_ext} = |Q_{C\_ext}| + |Q_{H\_ext}| = 3370W + 3370W = 6740W$$

T-H Diagram: $dT_{min} > dT_{min.set}$



T-H Diagram: Phase Change



Iteration

- Re-orientate flows until $dT_{min}>dT_{min,set}$
- Employ different heat exchangers
- Multiple scenario evaluation
- Cost benefit consideration
- Usually aided by computer software (e.g. ASPEN)