Introduction to Chemical and Environmental Engineering – Study Guide

Chemical Engineering Fundamentals
Credit to CBE245 for slides

As a chemical engineer you will encounter many types of processes and will be asked to design, operate or optimize a particular process (CBE Design Course)

What is a process?

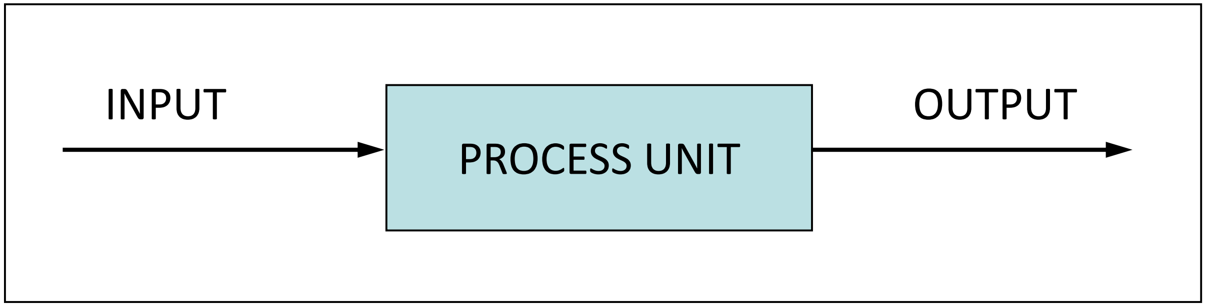
Process: an operation or series of operations that causes a physical or chemical change, thereby converting raw materials into products

Within any process there are **process streams**: input and output of a process unit; governed by conservation of mass and energy: What goes in must come out!

input may also be called feed stream

output may also be called the product stream

Process flowsheet: Input-Output Diagram

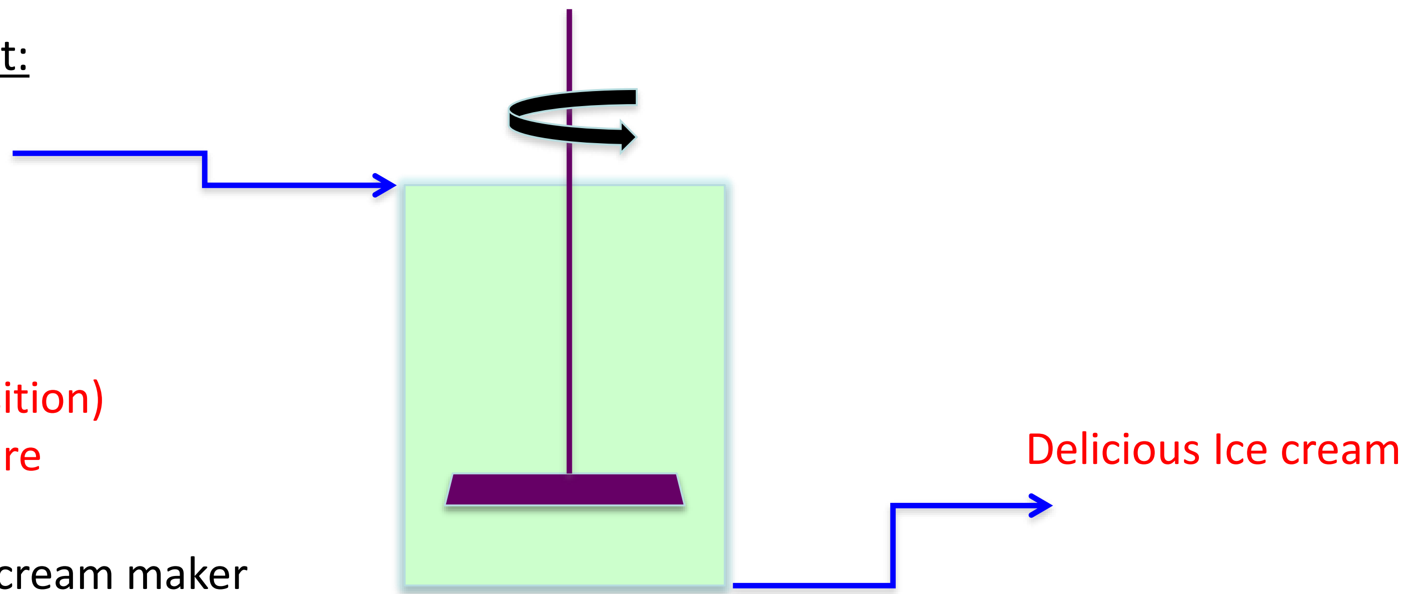


Process variables: variables to characterize the streams entering and leaving a process unit. What are some important process variables? **temperature, pressure, composition…**

Let’s take a look at a few examples of processes:

Consider ice-cream making at your favorite place (Thomas Sweets, Bent Spoon, etc…)

Process flowsheet:



Process unit: Ice cream maker

Process streams: input – cream, sugar, flavoring
output – ice cream

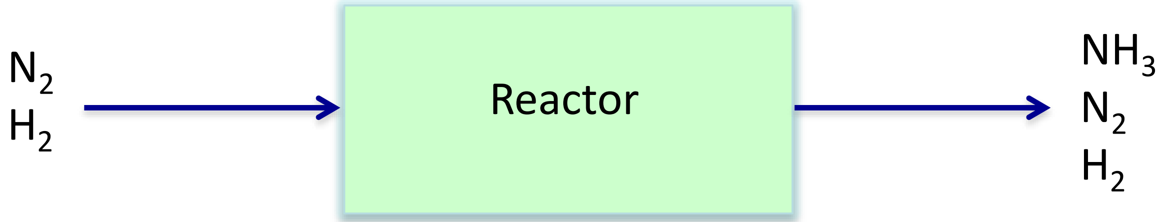
This is a batch process; it is characterized by chemical and physical changes without materials moving in or out, except at the beginning and at the end of a cycle.

The ingredients are fed into the batch reactor at the beginning of the cycle; ice-cream is removed at the end of the cycle.

Ammonia synthesis example:

[Recall that this is one of the top ten chemical engineering achievements; 35B lbs produced in 1995 (sixth largest chemical production)]

Chemical reaction: $N_{2(g)} + 3H_{2(g)} \rightarrow 2NH_{3(g)}$

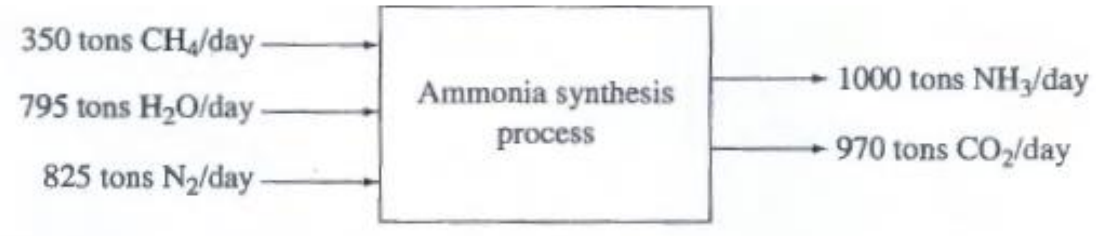


If the previous example was a batch process, what type of process is the above? It is a **continuous process** and is characterized by chemical and physical changes **with** material moving in and out

Process variables in this example includes:

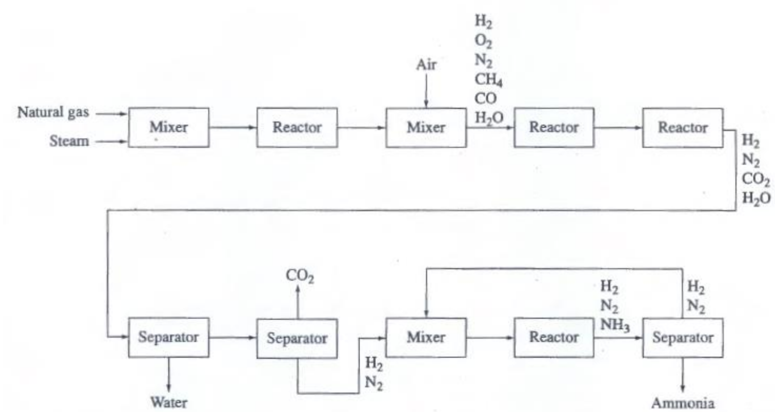
- Temperature of the inlet and outlet streams
- Pressure of the inlet and outlet streams
- Compositions of the inlet and outlet streams
- Total amount of material in the inlet and outlet streams

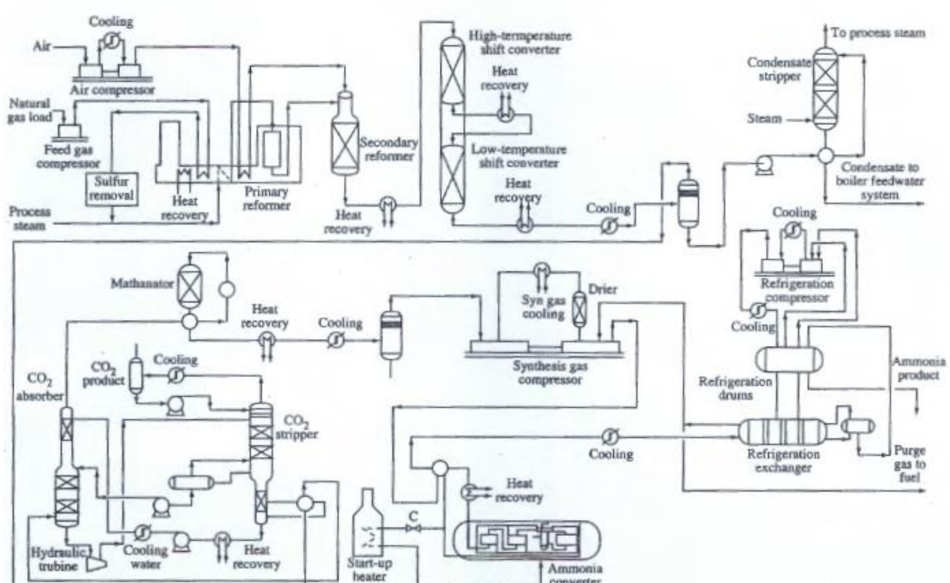
Ammonia Synthesis



Input-Output Diagram

Block Flow Diagram





Process Flow Diagram

As in the previous example, most process streams consist of a mixture of liquids or gases, or solution of one or more solutes in a liquid solvent.

* When discussing **<u>composition</u>** as a **<u>process variable</u>** we must think in terms of mass, volume, density, moles, etc.

density ≡ mass per unit volume; has dimensions of mass/length^3
[=] g/cm^3; kg/m^3; lb_m/ft^3

What can you do with density? Use it to determine volume of a given mass or vice versa…

<u>Density</u> – a material property but depends on T, P.
How does density change with T and P?

example: Density (ρ) of water at 4°C, 1 atm = 1.00000 g/cm^3
Density of water (liquid) at 0°C, 1 atm = 0.999868 g/cm^3
Density of water (liquid) at 100°C, 1 atm = 0.95838 g/cm^3

Water – an "anomaly"; volume expands as you cool from 4 to 0°C

* Most pure compounds – density decreases with increasing temperature (volume expansion)

* Density of many pure compounds, solutions, and mixtures can be found in standard references including the back of your text book.

Regarding density, in this class we will make the following assumptions (remember, get comfortable making assumptions!):

- solids and liquids are incompressible, so density is constant with pressure
- gases and vapors are compressible, so density changes with pressure

Specific volume ≡ volume occupied by a unit mass of the substance;
has dimensions of length^3/mass
(reciprocal density)

Specific gravity ≡ the ratio of the density of a substance to a reference density of a reference substance at specific conditions; dimensionless

$$\boxed{SG \equiv \frac{\rho(T,P)}{\rho_{ref}(T,P)}}$$

For solids and liquids, the most common reference is water at 4^{o}C, 1 atm:

$$\rho_{water(l)}\ (4^oC,\ 1\ atm) = 1.000\ g/cm^3 = 1000.\ kg/m^3 = 62.43\ lb_m/ft^3$$

Typically, specific gravity is expressed as:

$$SG = 0.6^{20^\circ}_{4^\circ}$$

20^{o}C = T of sub.
4^{o}C = T of ref.

What is a mole? I am sure everyone can answer this question?

A certain amount of material corresponding to a specific number of molecules, atoms, electrons, or any specified type of particles?

The word mole is derived from the Latin word *moles* meaning *heap* or *pile*. So basically a mole is a large heap of particles.

Official definition: the amount of a substance that contains as many entities as there are atoms in 12 gm of carbon. Number of entities = $6.023 \cdot 10^{23}$ atoms

g-mole (mol) – amount of substance whose mass is expressed in grams;
is equivalent to the molecular weight of the substance (in grams)

Example: CO has a molecular weight of 28 gm/mol – 1 mol of CO contains 28 gm of CO and 1 mol of CO contains $6.023 \cdot 10^{23}$ molecules

CGS	SI	American
g	k_g	lb_m
mol	kmol	lb-mole
g/mol	k_g/kmol	lb_m/lb-mole

Lets look at an example:

How many of each of the following are contained within 100 gm of CO_2? M_w = 44.01 g/mol (44.01 lb_m/lb-mol, 44.01 k_g/kmol)

a) mol of CO_2?

$$100.0gm \times \frac{1molCO_2}{44.01gmCO_2} = 2.273molCO_2$$

b) lb-moles of CO_2?

$$100.0gm \times \frac{1lb_m}{453.6gm} \times \frac{1lbmol}{44.01lb_m} = 5.011 \times 10^{-3} lbmolCO_2$$

c) mol of O?

$$100.0gm \times \frac{1molCO_2}{44.01gm} \times \frac{2molO}{1molCO_2} = 4.546molO$$

d) molecules of CO_2?

$$2.273molCO_2 \times \frac{6.02 \times 10^{23} molecules}{1mol} = 1.37 \times 10^{24} molecules$$

Defining Composition:

A mass fraction is the mass of particular compound in a mixture divided by the total mass

$$x_A = \frac{\text{mass of A}}{\text{total mass}} \ [=] \ \frac{\text{k}_\text{g} \text{ A}}{\text{total k}_\text{g}} \ [=] \ \frac{\text{g A}}{\text{total g}} \ [=] \ \frac{\text{lb}_\text{m} \ A}{\text{total lb}_\text{m}}$$

mole fraction:

$$y_A = \frac{\text{moles of A}}{\text{total moles}} \ [=] \ \frac{\text{k}_\text{g}\text{mol A}}{\text{total k}_\text{g}\text{mol}} \ [=] \ \frac{\text{gmol A}}{\text{total gmol}} \ [=] \ \frac{\text{lb}_\text{m}\text{mol } A}{\text{total lb}_\text{m}\text{mol}}$$

volume fraction:

$$v_A = \frac{\text{volume of A}}{\text{total volume}} \ [=] \ \frac{\text{m}^3 \text{ A}}{\text{total m}^3} \ [=] \ \frac{\text{cm}^3 \text{ A}}{\text{total cm}^3} \ [=] \ \frac{\text{ft}^3 \ A}{\text{total ft}^3}$$

* Fractions are <u>unitless!</u>

Generalizations:

• solids and liquids generally go by mass or mole fractions
• gases and vapors generally go by mole or volume fractions

Chemical engineers are not only interested in content (composition) but are also interested in quantity as most processes involve the movement of material from one point to another.

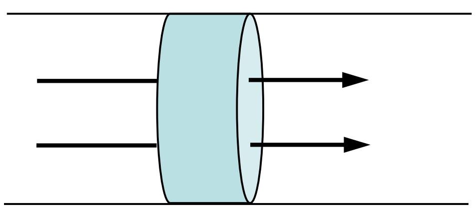
Where is material moved? Between process units or between production facilities, etc..

We are interested in the rate at which materials are being transported through the process line.

$$\text{mass flow rate} = \dot{m} \equiv \frac{\text{mass}}{\text{time}}$$

$$\text{volumetric flow rate} = \dot{V} \equiv \frac{\text{volume}}{\text{time}}$$

Suppose a fluid (gas or liquid) flows in a cylindrical pipe shown below, and the shaded area represents a section perpendicular to flow. If the mass flow rate is known, then every sec *m* kilograms pass through the area. If the volumetric flow rate is known, then every second *V* cubic meters of fluid pass through the area. Are the two *m* and *V* independent?



$$\boxed{\text{Density} = \rho \equiv \frac{m}{V} \equiv \frac{\dot{m}}{\dot{V}}}$$

Mass flow rate must be known for many calculations, yet in practice volumetric flow rate is measured.

Example: Conversion between mass fraction and mole fraction

An industrial-strength drain cleaner contains 5.00 kg of water and 5.00 kg of NaOH. What are the mass fractions and mole fractions of each component in the drain container?

You are giving the masses, so it is easy to calculate the mass fractions. The masses have to be converted in moles, so that mole fractions can be determined.

Conversion of masses to moles…..

$$5.00 kgH_2O \times \frac{1 kgmolH_2O}{18.0 kgH_2O} = 0.278 kgmolH_2O$$

$$5.00 kgNaOH \times \frac{1 kgmolNaOH}{40.0 kgNaOH} = 0.125 kgmolNaOH$$

Calculate mass and mole fractions…..

m_{H2O} = 5kg / 10 kg = 0.5

m_{NaOH} = 5kg / 10 kg = 0.5

n_{H2O} = 0.278 / 0.278 + 0.125 = 0.69

n_{NaOH} = 0.125 / 0.278 + 0.125 = 0.31

Example : A mixture of gases has the following composition by mass:

O_2	16%
CO	4.0%
CO_2	17%
N_2	63%

What is the molar composition?

Set a basis of 100 gm of mixture

Mass fraction of O_2 = 16/100 = 0.16 = Xo_2

Mass of O_2 = mo_2 = Xo_2 * m_{total} = 0.16 *100 = 16 gm

Mol of O_2 = no_2 = mo_2/M_wo_2 = 16gm / 32gmmol^{-1} = 0.5 mol

Perform the same calculations for CO, CO_2, and N_2

Mol of CO = 0.143

Mol of CO_2 = 0.386

Mol of N_2 = 2.250

Total moles = $mol_{CO} + mol_{CO2} + mol_{N2} + mol_{O2} = 3.279$

Molar composition = $y_i = n_i/n_{total}$

y_{O2} = 0.5/3.279 = 0.150; y_{CO} = 0.044; y_{CO2} = 0.120; y_{N2} = 0.690

Environmental Engineering Fundamentals

Credit to CEE304 for slides/information

Water consumption refers to the permanent withdrawal (no longer available in its original form, i.e. evaporation) of water from its source, while water withdrawal refers to water merely withdrawn or diverted from its source.

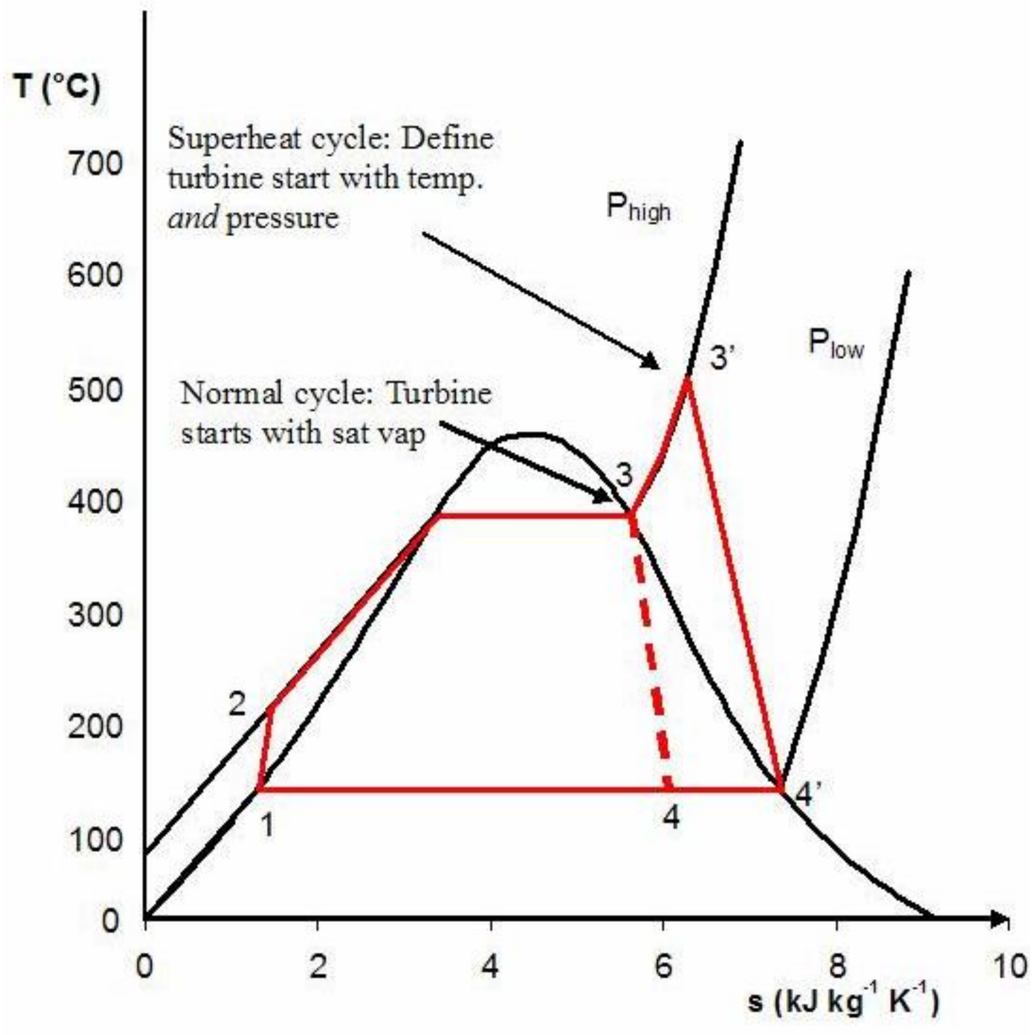
Equations

Efficiency: $$\eta = \frac{Energy_{out}}{Energy_{in}}$$

Energy: $$\frac{Power}{Area} = \frac{Energy}{(Time)(Area)}$$

$$\left(\frac{W}{m^2}\right) = \left(\frac{J}{s\,m^2}\right)$$

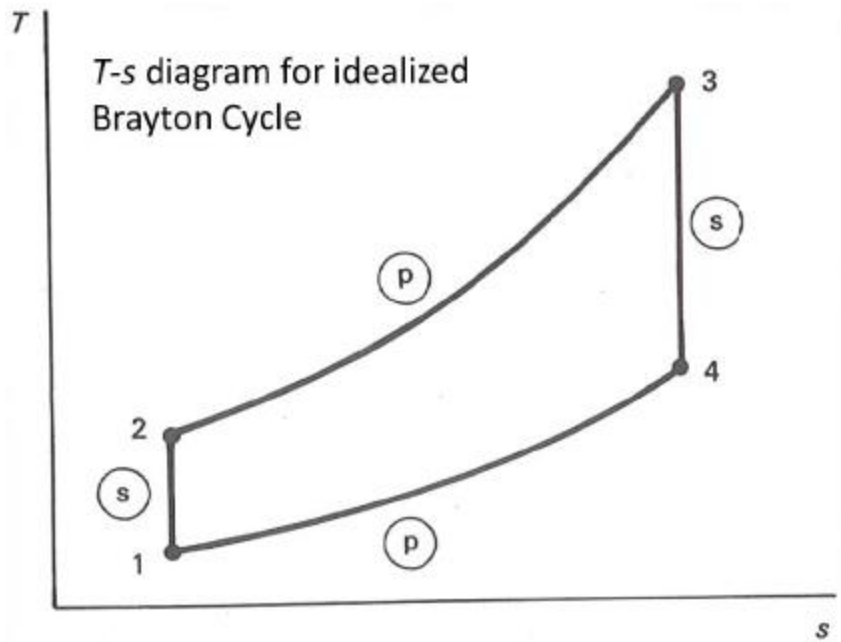
Rankine cycle

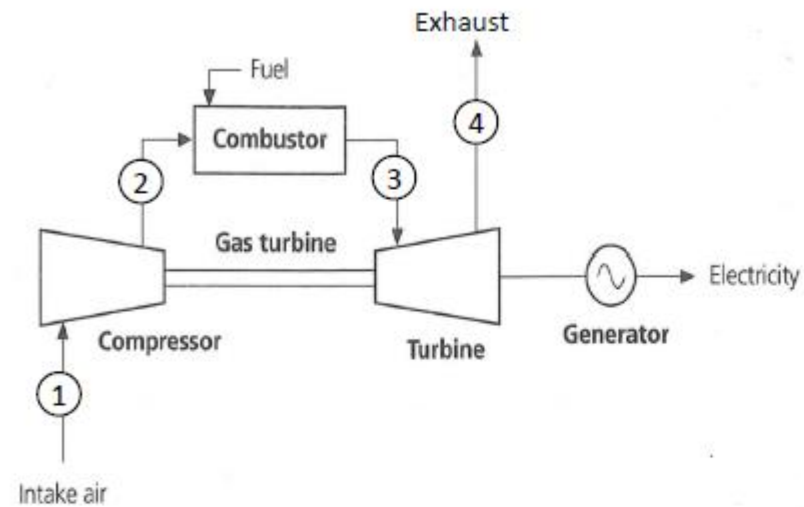


T-s diagram

for steam turbine

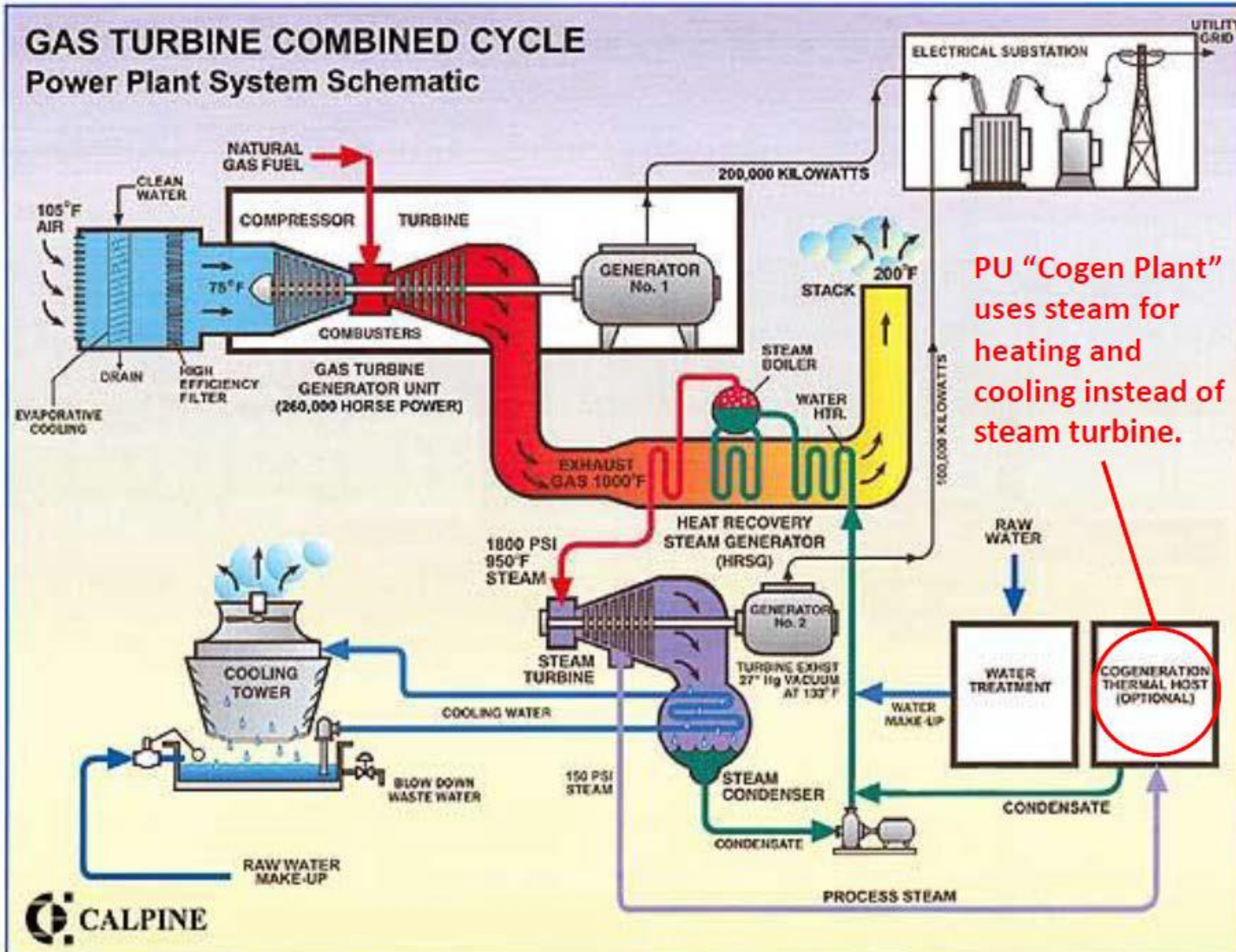
Brayton cycle



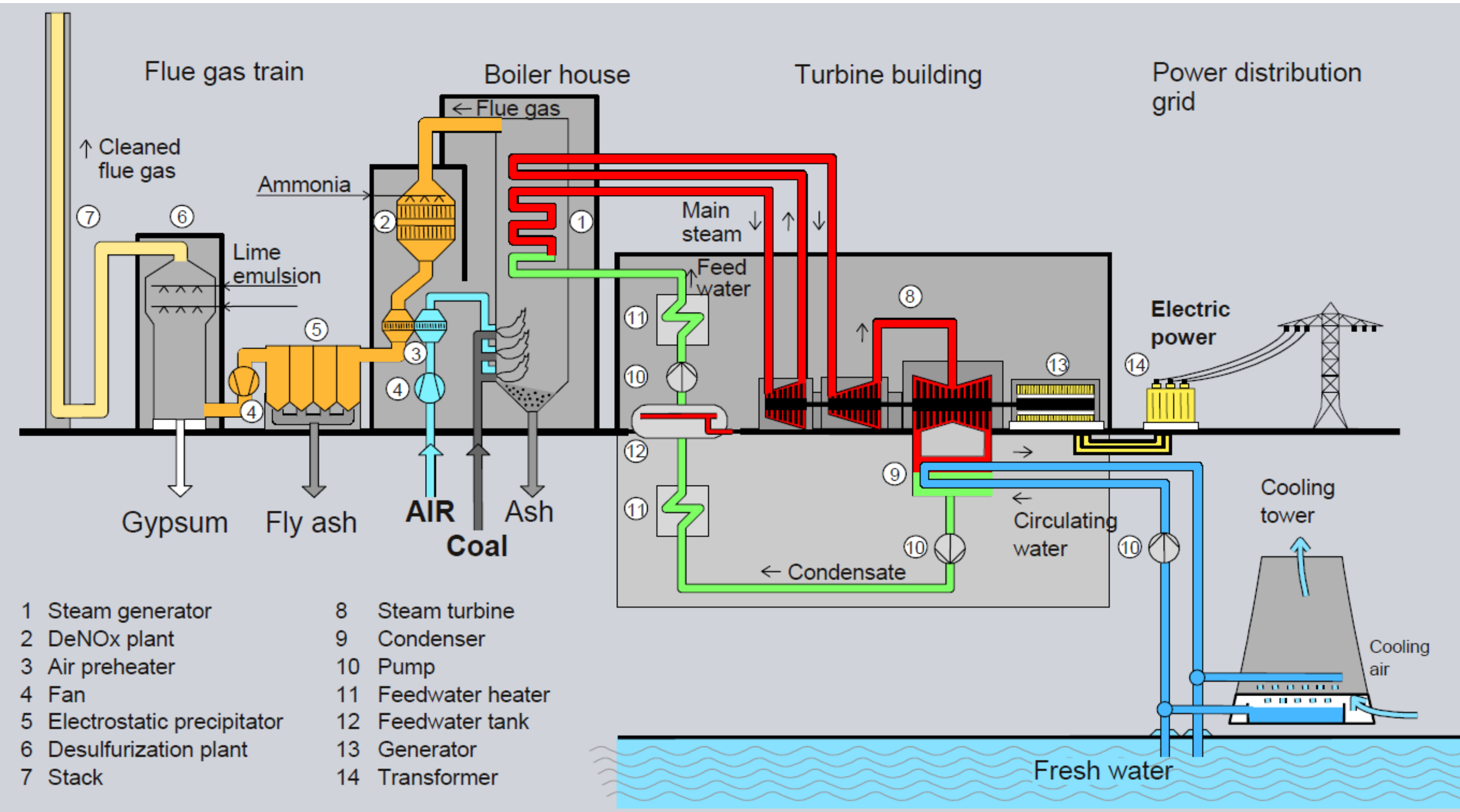


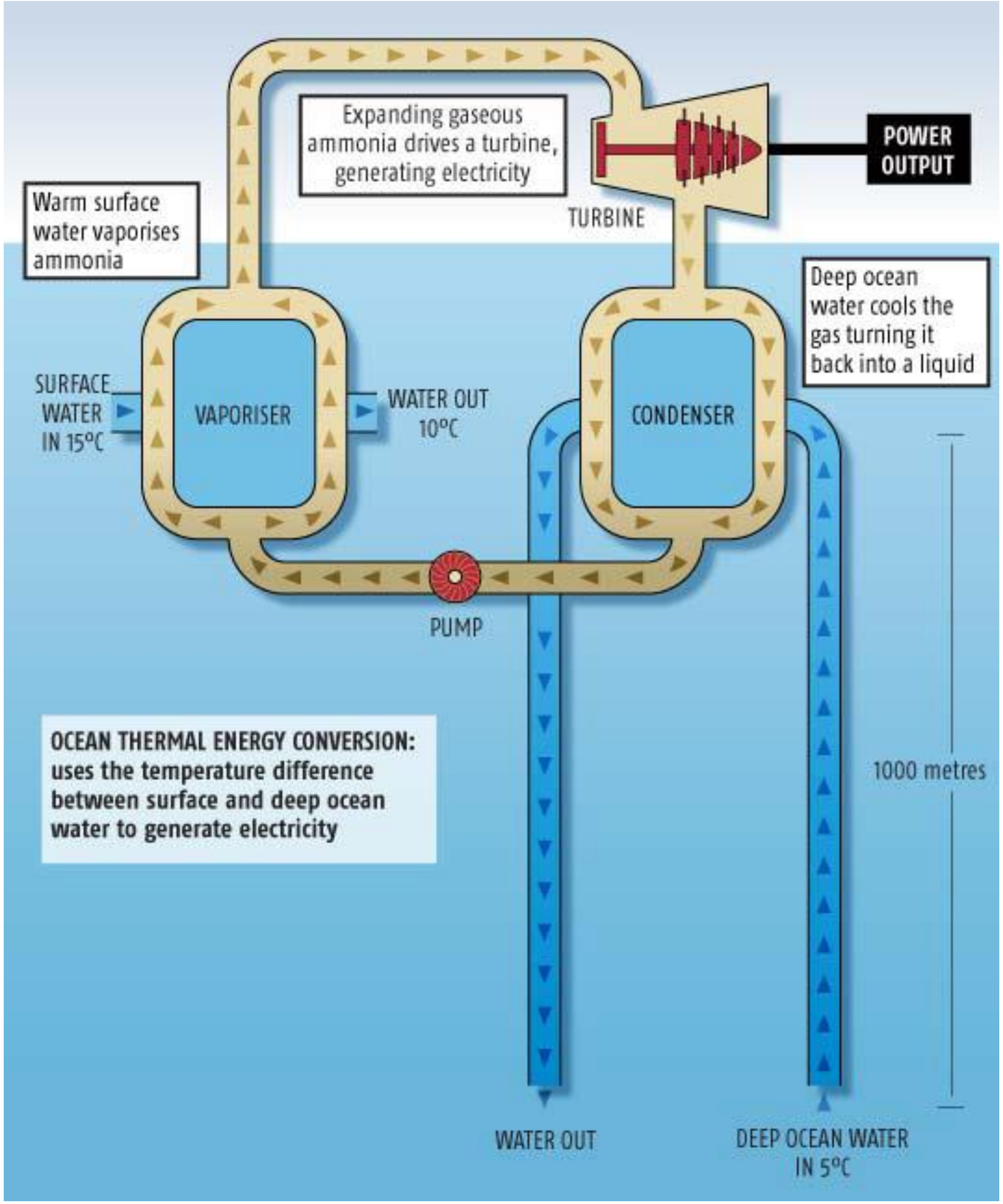
Ideal (Air) Brayton Cycle

1 → 2: Isentropic compression
2 → 3: Isobaric heat addition
3 → 4: Isentropic expansion
4 → 1: Isobaric heat rejection


GAS TURBINE COMBINED CYCLE
Power Plant System Schematic
ELECTRICAL SUBSTATION
UTILITY GRID
NATURAL GAS FUEL
200,000 KILOWATTS
CLEAN WATER
105°F AIR
COMPRESSOR
TURBINE
75°F
GENERATOR No. 1
COMBUSTERS
STACK
200°F
PU "Cogen Plant" uses steam for heating and cooling instead of steam turbine.
DRAIN
HIGH EFFICIENCY FILTER
EVAPORATIVE COOLING
GAS TURBINE GENERATOR UNIT (260,000 HORSE POWER)
STEAM BOILER
WATER HTR.
100,000 KILOWATTS
EXHAUST GAS 1000°F
HEAT RECOVERY STEAM GENERATOR (HRSG)
1800 PSI 950°F STEAM
RAW WATER
GENERATOR No. 2
STEAM TURBINE
TURBINE EXHST 27" Hg VACUUM AT 133° F
COOLING TOWER
COOLING WATER
WATER MAKE-UP
WATER TREATMENT
COGENERATION THERMAL HOST (OPTIONAL)
BLOW DOWN WASTE WATER
150 PSI STEAM
STEAM CONDENSER
CONDENSATE
CONDENSATE
RAW WATER MAKE-UP
PROCESS STEAM
CALPINE

Coal-Fired Power Plant

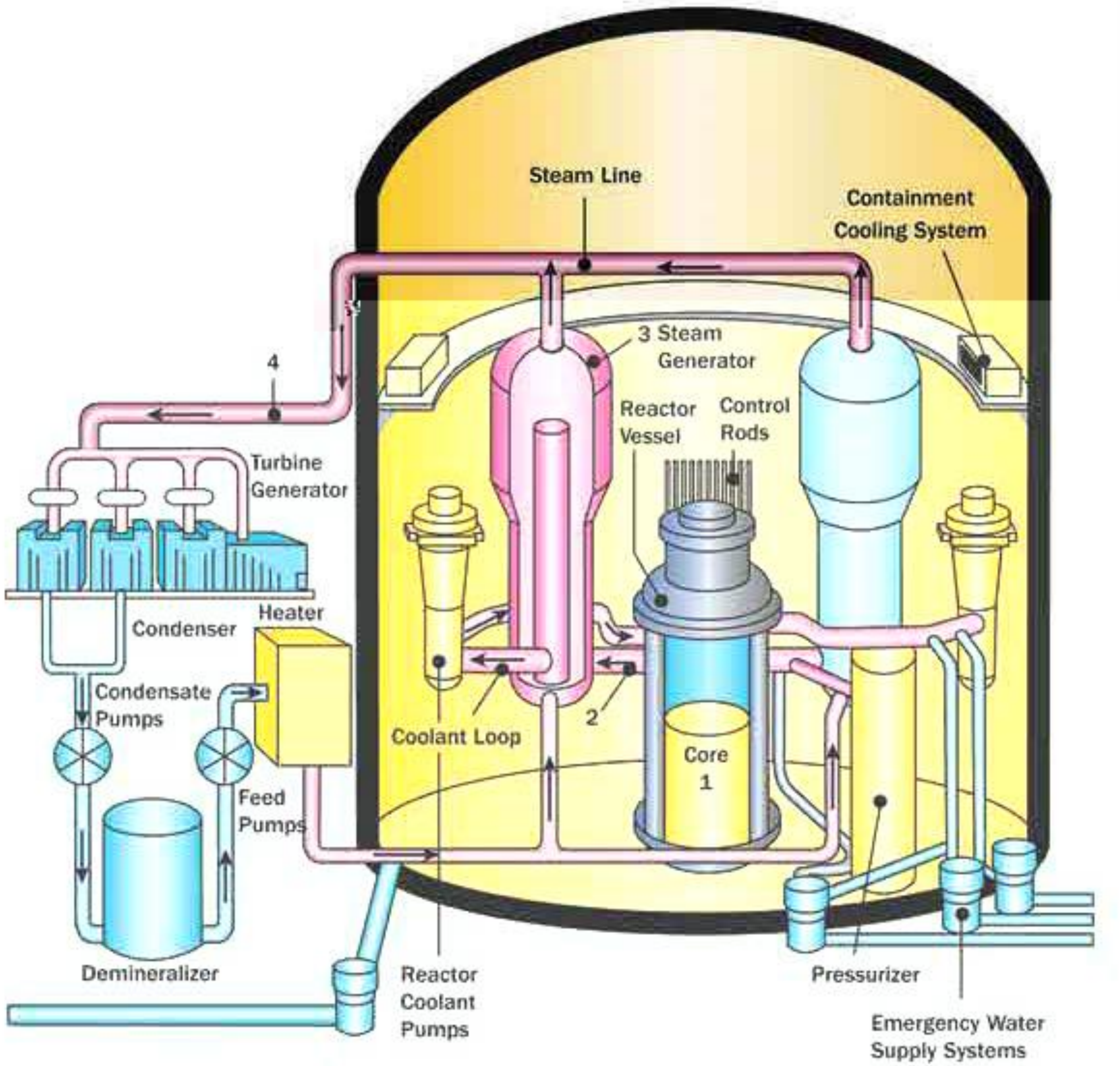




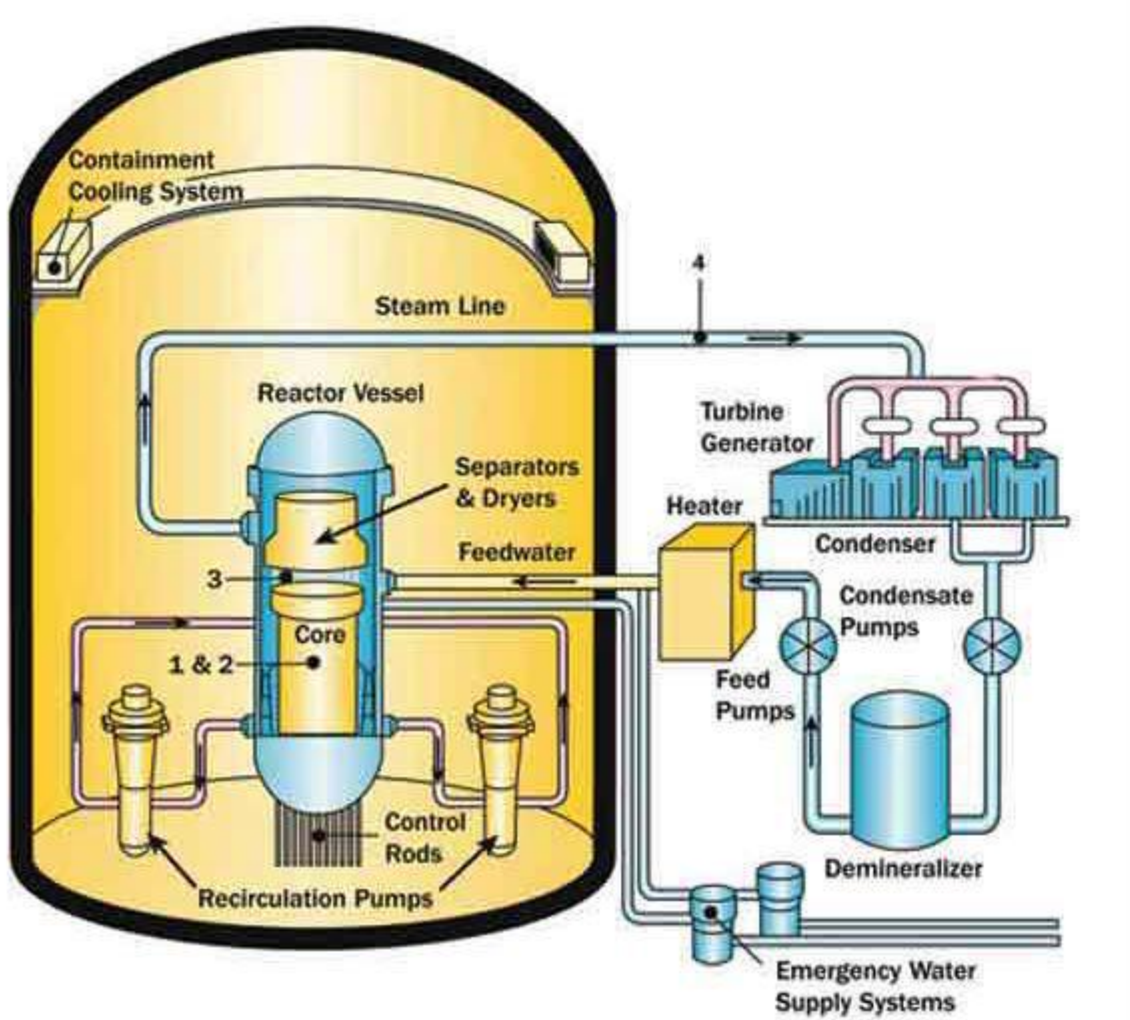
Expanding gaseous ammonia drives a turbine, generating electricity
POWER OUTPUT
TURBINE
Warm surface water vaporises ammonia
Deep ocean water cools the gas turning it back into a liquid
SURFACE WATER IN 15ºC
VAPORISER
WATER OUT 10ºC
CONDENSER
PUMP
OCEAN THERMAL ENERGY CONVERSION: uses the temperature difference between surface and deep ocean water to generate electricity
1000 metres
WATER OUT
DEEP OCEAN WATER IN 5ºC

OTEC

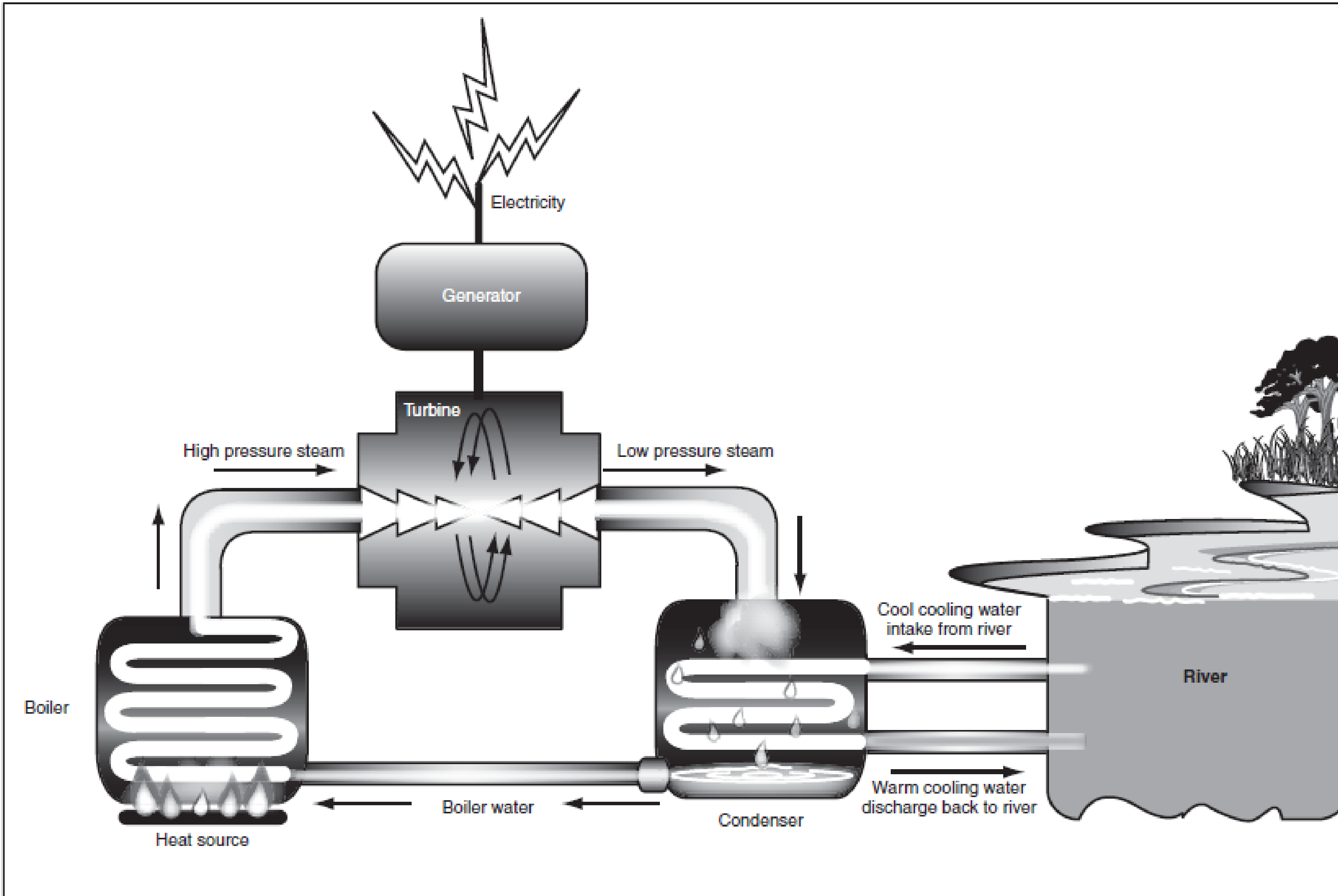
Pressurized Water Nuclear Reactor



Boiling Water Nuclear Reactor



Once-Through Cooling Water System



Wet Recirculating Cooling System