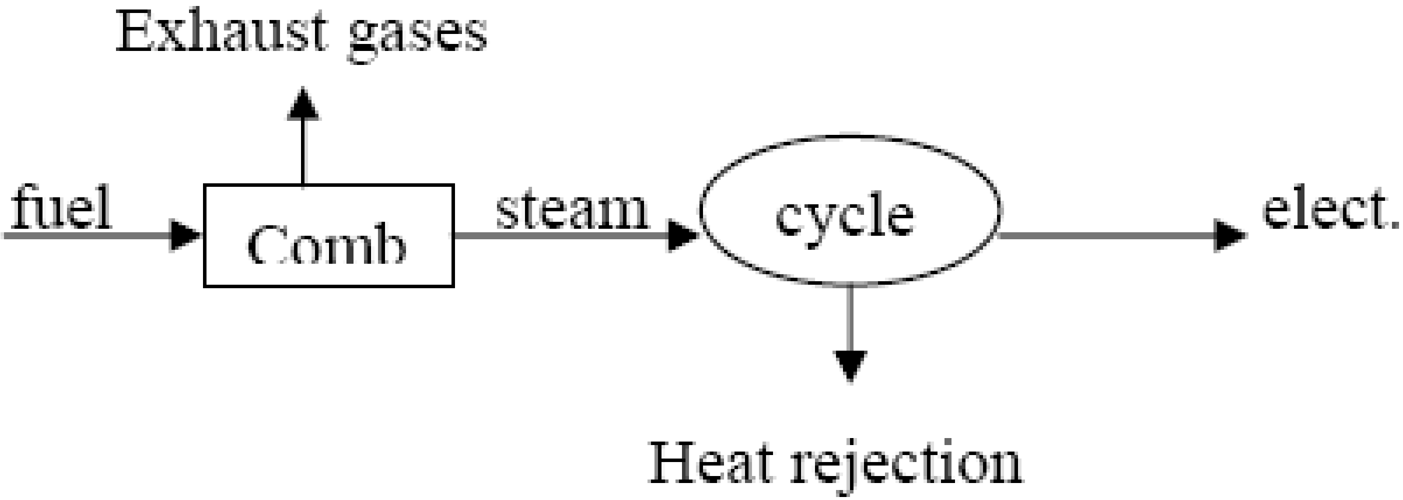
Energy Conversion
Chapter Five

Environment Impact of Power Generation

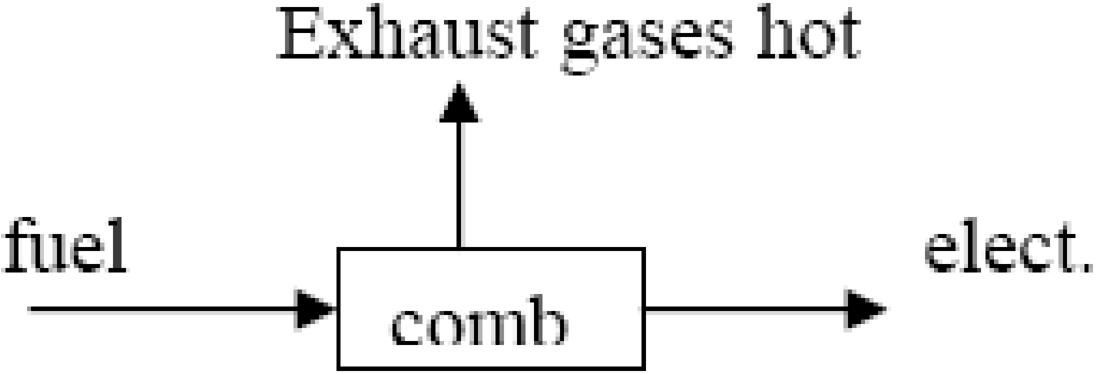
Introduction

- Power plant involves many source of environmental pollution.
- Starting from fuel preparation, such as open pit mining.
- Transport of petroleum and spills associated with transportation.
- Combustion of fuel produces some polluting gases and particles.
- Heat rejection from the thermodynamic power cycle is a source of thermal pollution.
- Life cycle Analysis concept.

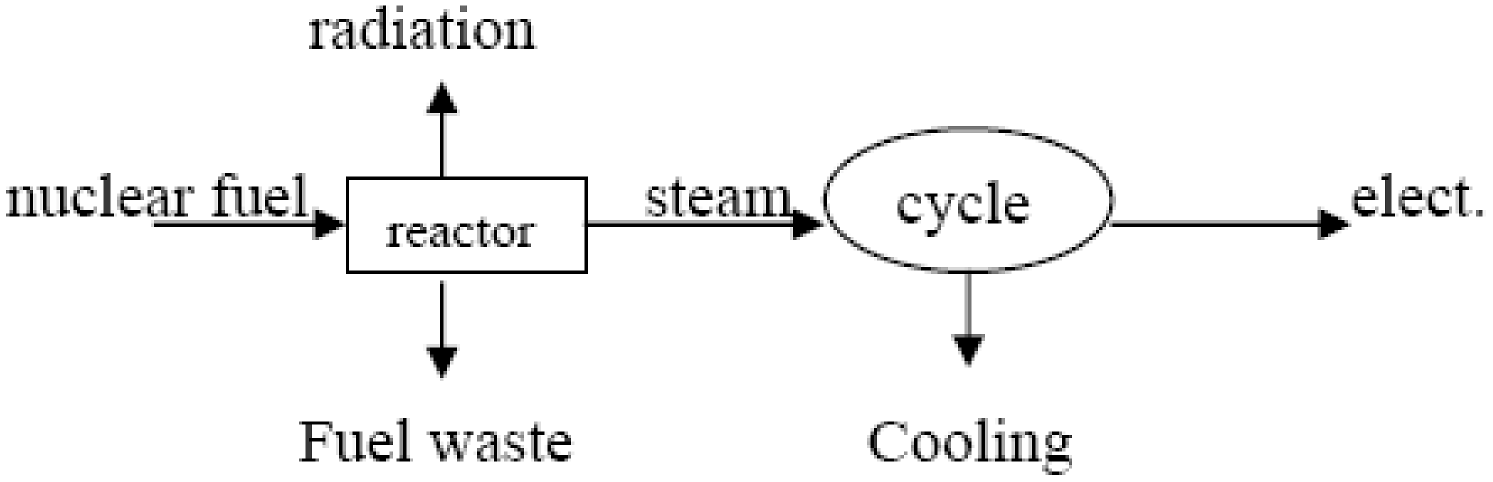
Steam power plant



Gas Turbine



Nuclear power plant



Environmental Standards

- In order to reduce environmental impact of power generation, industrialized countries have set forth some limits on the pollution emission and strict safety precaution especially for nuclear power plants.
- The price paid to reduce pollution is very concerning to the power generating companies.
- Opposition for pollution from people NGO push’s for a more strict control and cleaning of the environment.

Power generation pollution

- Three main sources of power generation pollution will be discussed here:
  - Gaseous pollution.
  - Thermal pollution.
  - Nuclear radiation and waste.

Gaseous Pollution and Control

- Combustion of fossil fuels generates a variety of undesired and harmful gasses, such as
  - SOx (SO2 , SO3) ,
  - NOx ,
  - CO , CO2 ,
  - aldehydes and hydrocarbons.
- Adding to this particles (dust) of various sizes, from ash and their products that are produced in the combustion process.

SOx Effects

- SO_2 & SO_3: are toxic and cause irritation to mucus membrane.
- SO_2 dissolves in water vapor to form acid, and interacts with other gases and particles in the air to form sulfates and other products that can be harmful to people and their environment.
- Also cause the acid rain

$$SO_3 + H_2O \rightarrow H_2SO_4$$

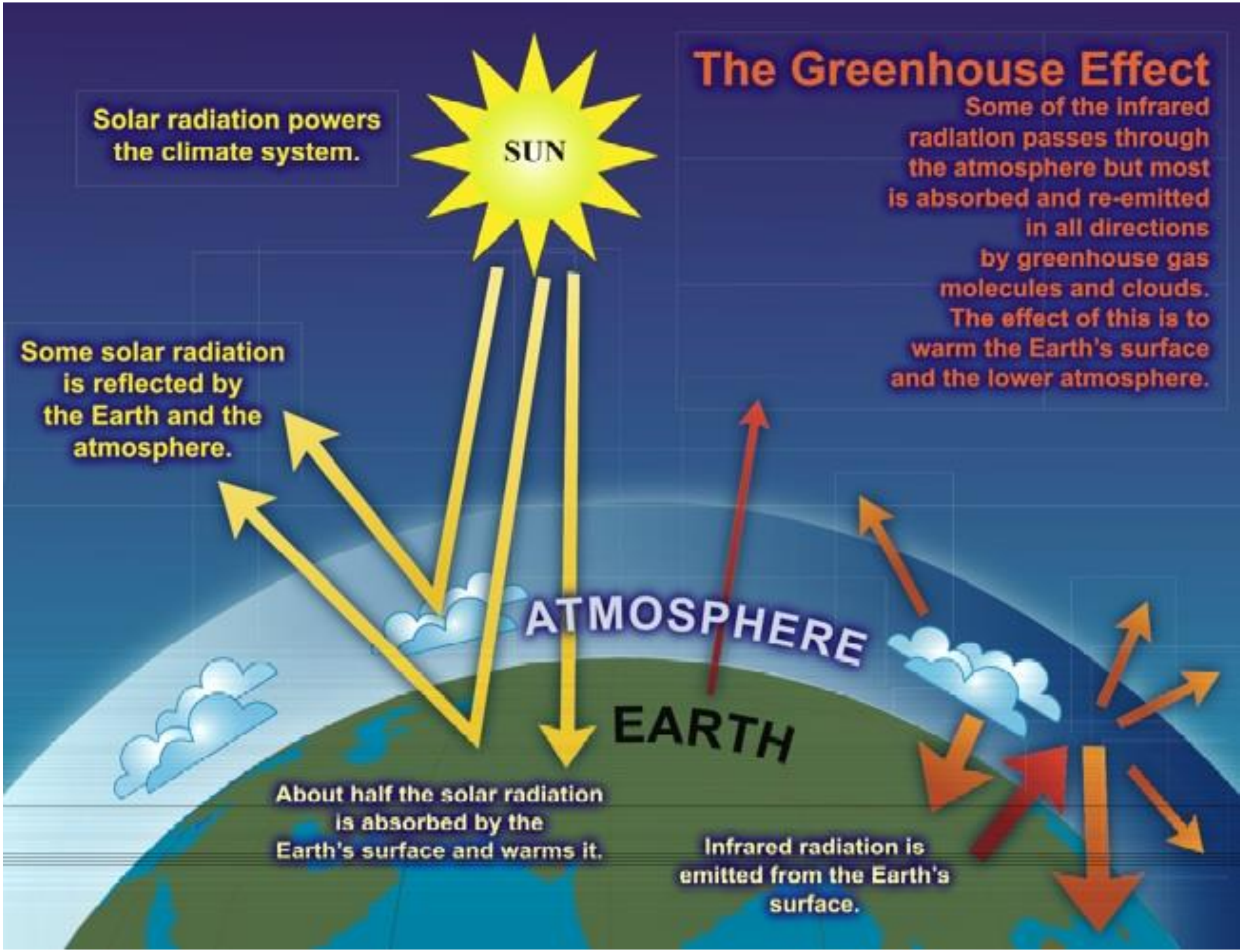
which is harmful to vegetation and highly corrosive .

Health and environmental impacts of SO2

- Respiratory effects: peak levels of SO2 in the air can cause temporary breathing problems for people with asthma who are active outdoor. Long term exposure to high levels and particles of SO2 cause respiratory illness and aggravate existing heart disease.
- Acid rain: SO2 and nitrogen oxides react with other substances in the air to form acids which fall to earth as rain, fog, snow or dry particles.
- Plant and water damage: acid rain damages forests and crops, change the makeup of soil, and make lakes and streams acidic and unsuitable for fish.

Greenhouse effect

- CO2: dry air contains 0.035%while it increases a bout 4% annually (1750 ; 280 ppm, 1980; 340 ppm, 1998; 351 ppm).
- CO2 works as a green house
  - allowing short wave sun radiation and
  - absorbing and bouncing long wave terrestrial radiation ,
  - hence prevent earth cooling by thermal radiation.
- which leads to increase in mean earth temperature.


The Greenhouse Effect
Some of the infrared radiation passes through the atmosphere but most is absorbed and re-emitted in all directions by greenhouse gas molecules and clouds. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation powers the climate system.
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
ATMOSPHERE
EARTH
About half the solar radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

CO as pollutant

- Carbon monoxide is a colorless odorless gas.
- The dominant source of CO is incomplete combustion of carbonaceous fuel.
- In ambient air a major source is automobile exhaust, consisting 56% of the total CO sources , other non-road engines and equipment contribute about 22% ,
- other sources of CO emission include industrial processes such as metal processing and chemical manufacturing, residential wood burning natural sources such as forest fires. Woodstoves, gas stoves, cigarette smoke, unvented gas and kerosene space heaters are sources of CO indoors.
- The highest levels of CO in the outside air typically occur during the colder months of the year. The air pollutants becomes trapped near the ground beneath a layer of warm air.

CO effects

- CO binds with the hemoglobin in red blood cells, impairing the oxygen-carrying capacity of the blood. The affinity of hemoglobin for CO is about 250 times as high as for oxygen. It also reduces the effectiveness of O2 delivery to tissues and organs.
- Exposure to elevated CO levels can impair visual perception, work capacity, learning ability, and performance of complex tasks. At high levels it is life threatening.

NOx

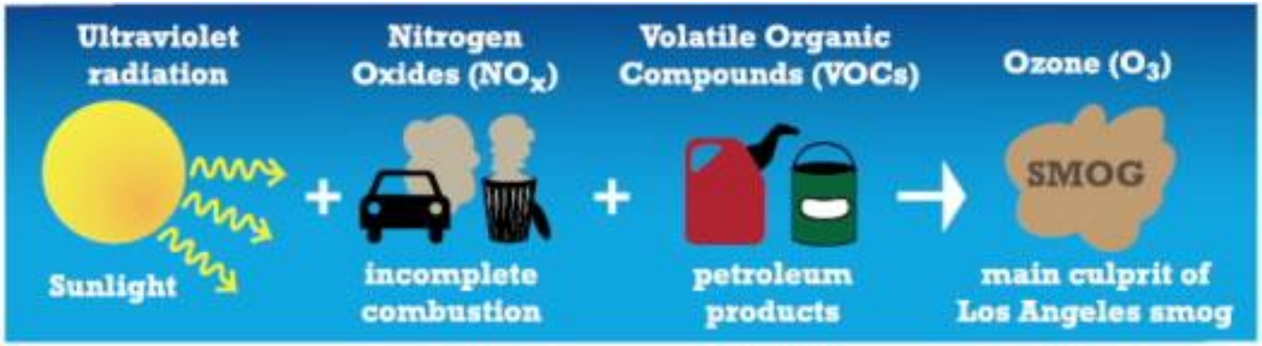
- NO_2 is a secondary pollutant formed by the oxidation of nitric oxide in the atmosphere.
- NO is a combustion by product.
- The sum of NO and NO_2 plus other typically minor oxides of nitrogen is termed NO_x.
- In the atmosphere, NO is oxidized to NO_2 by reaction with ozone and with radicals that contain an O_2 group.
- The primary sources of NO_x are motor vehicles(49%), electric utilities (27%), and other industrial , commercial and residential sources (19%) that burn fuels.

NOx effects

- NOx causes a wide variety of health and environmental impacts because of various compounds and derivatives in the family of nitrogen oxides, including nitrogen dioxide, nitric acid, nitrous oxide, nitrates and nitric acid.
- Ground level ozone (smog) is formed when NOx and volatile organic compounds react in the presence of heat and sunlight. This smog trigger serious respiratory problems.
- Acid rain- NOx along with sulfur oxide react with other substances in the air to form acids which fall to earth as rain, fog, snow or dry particles. Acid rain damages causes deterioration of cars, buildings and historical monuments, and causes lakes and streams to become acidic and unsuitable for many fish.
- Visibility impairment- nitrate particles and nitrogen dioxide can block the transmission of light, reducing visibility in urban areas.

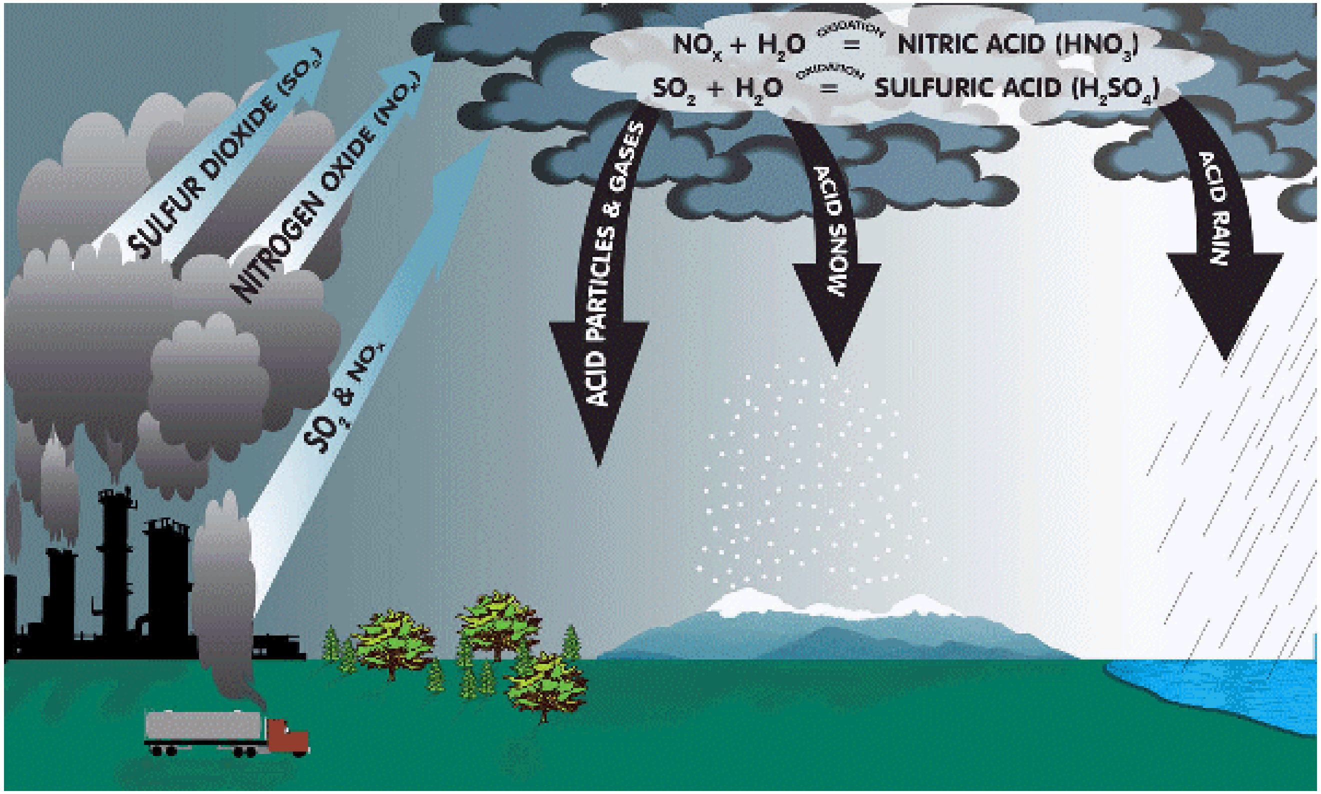
Smog

- The word "smog" was coined of the words smoke and fog to refer to smoky fog.
- This kind of visible air pollution is composed of nitrogen oxides, sulfur oxides, ozone, smoke or particulates among others (less visible pollutants include carbon monoxide, CFCs and radioactive sources).



Acid rain formation

Acid rain is rain with acidity lower than ‘’PH 5.6’’. neutral PH = 7, highly acidic 0, in USA and Europe rain has a PH 4.0.



Particulates

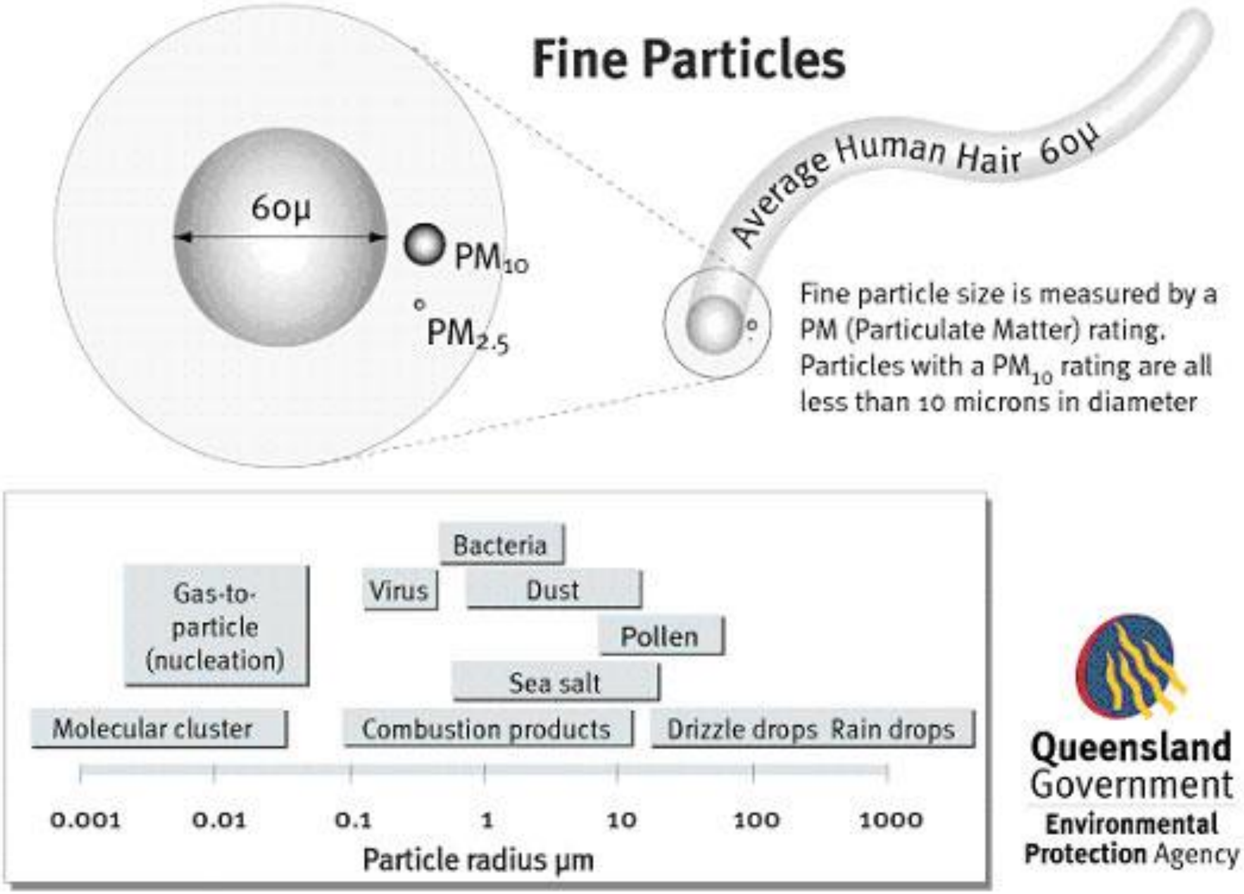
- Particulates:
  - harmful to animals and human,
  - cause breathing problems,
  - as well as blanket the sun radiation.
- Acid rain is rain with acidity lower than ‘’PH 5.6”. neutral PH = 7, highly acidic 0, in USA and Europe rain has a PH 4.0.

Particulates

- Coarse particles are mainly primary pollutants, with dominant sources that include;
    - dust from roads, construction, and agricultural emissions. Wind erosion is another source.
    - Industrial emissions are significant sources of both coarse and fine particles.
    - A major transportation source of fine particles is diesel soot.
    - Residential wood smoke in a notable source of fine particles.

Particulate size

Fine Particles



Fine particle size is measured by a PM (Particulate Matter) rating. Particles with a PM_{10} rating are all less than 10 microns in diameter

Queensland
Government
Environmental
Protection Agency

Health and environmental impacts of PM

- Health effects: Many scientific studies have linked breathing PM to a series of significant health problems, including: aggravated asthma, increases respiratory symptoms like coughing and difficult or painful breathing, and chronic bronchitis. Decreased lung function.
- Visibility impairment: PM is the major cause of reduced visibility.
- Atmospheric deposition: particles can be carried over long distances by wind and then settle on ground or water.
- Aesthetic damage: soot a type of PM stains and damages stone and other materials including culturally important objects and monuments.

Particles Standards

- Two standards apply to particle matter in outdoor air. The PM10 standard limits the mass concentration of airborne particles whose aerodynamic diameter is less than 10 µm. PM2.5 standard applies to particles with aerodynamic diameter smaller than 2.5 m.
- The aerodynamic diameter is the diameter of a spherical particle with the density of water that exhibits the same inertial transport properties as the particle in question.

Emission standards EPA

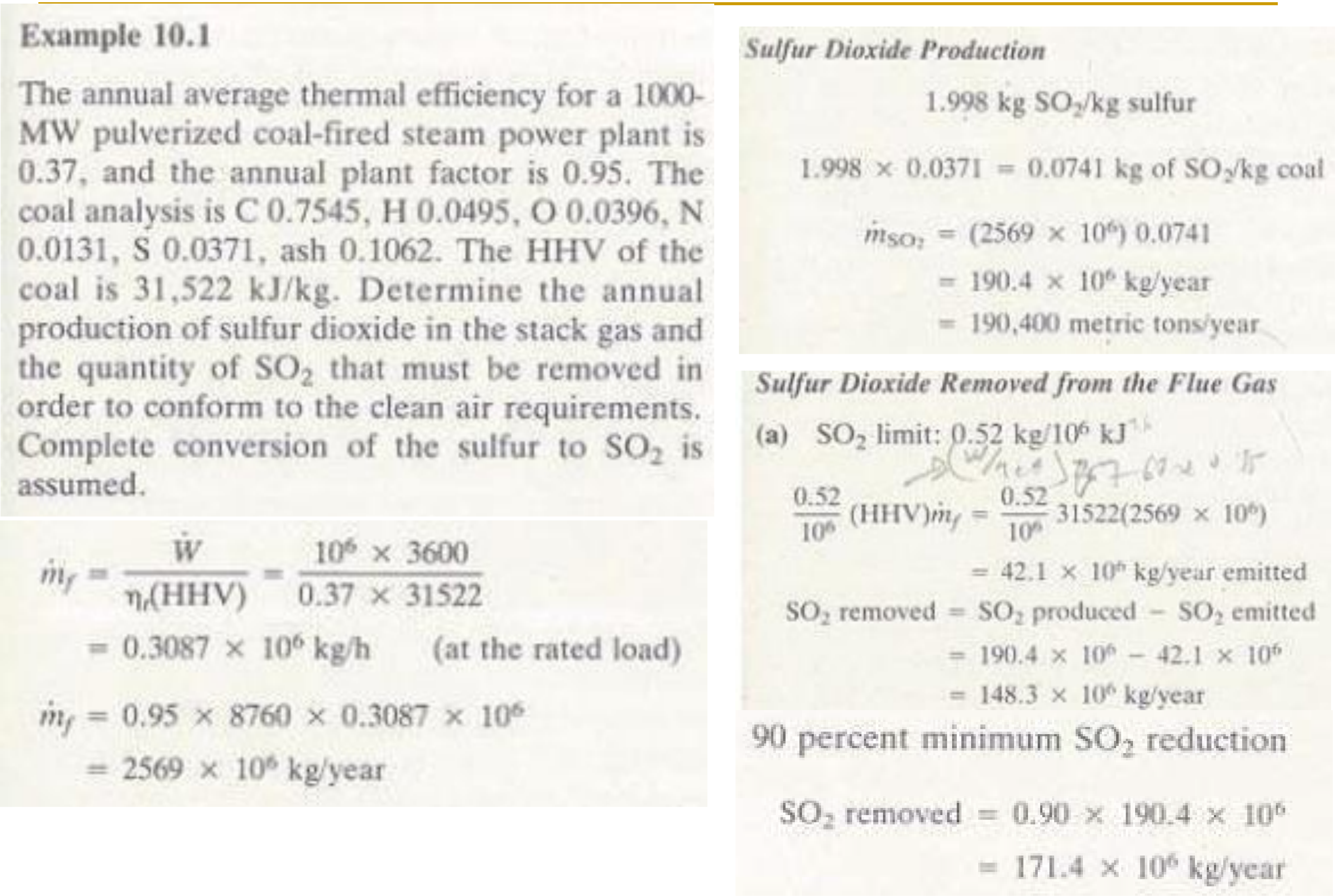
- Government has set some limits in the above pollutants gases emission. For example, the Environment Protection Agency EPA in the USA has defined the danger level of the air containment of the above gases.
- Two standards are to be observed.
  - ❑ Emission rate, or concentration of pollutant emitted from stack.
  - ❑ An ambient concentration regulates the concentration of pollutants at ground level.

Stack emission standards

- Stack emission standards are in 1lbm pollutant /106 Btu or kg pollutant / 106kJth
- EPA stock emission standards according to 1970 Amendment, the discharge limitations are as follow in kg/10^6kJth.
- SO2: coal 0.52, oil 0.34
- NOx: coal 0.30, oil 0.13, and gas 0.086
- Particulates: Coal, oil and gas 0.043

Stack emission standards

- Revised standards of 1978 requires a minimum reduction of 90% in the SOx emission for plants burning high sulfur coal & 70% for those burning low sulfur coal.
- In the 1970 standards a removal of 75% of the high sulfur coal while no control were required for low sulfur coal.
- *Work example 10.1 p.355 Sorenson.*



Example 10.1

The annual average thermal efficiency for a 1000-MW pulverized coal-fired steam power plant is 0.37, and the annual plant factor is 0.95. The coal analysis is C 0.7545, H 0.0495, O 0.0396, N 0.0131, S 0.0371, ash 0.1062. The HHV of the coal is 31,522 kJ/kg. Determine the annual production of sulfur dioxide in the stack gas and the quantity of SO_2 that must be removed in order to conform to the clean air requirements. Complete conversion of the sulfur to SO_2 is assumed.

$$\dot{m}_f = \frac{\dot{W}}{\eta_t(\text{HHV})} = \frac{10^6 \times 3600}{0.37 \times 31522}$$

$$= 0.3087 \times 10^6 \text{ kg/h} \qquad \text{(at the rated load)}$$

$$\dot{m}_f = 0.95 \times 8760 \times 0.3087 \times 10^6$$

$$= 2569 \times 10^6 \text{ kg/year}$$

Sulfur Dioxide Production

$$1.998 \text{ kg } SO_2/\text{kg sulfur}$$

$$1.998 \times 0.0371 = 0.0741 \text{ kg of } SO_2/\text{kg coal}$$

$$\dot{m}_{SO_2} = (2569 \times 10^6)\, 0.0741$$

$$= 190.4 \times 10^6 \text{ kg/year}$$

$$= 190{,}400 \text{ metric tons/year}$$

Sulfur Dioxide Removed from the Flue Gas

(a) SO_2 limit: 0.52 kg/10^6 kJ

(W/η_t) 8760 × 0.95

$$\frac{0.52}{10^6}(\text{HHV})\dot{m}_f = \frac{0.52}{10^6} 31522(2569 \times 10^6)$$

$$= 42.1 \times 10^6 \text{ kg/year emitted}$$

$$SO_2 \text{ removed} = SO_2 \text{ produced} - SO_2 \text{ emitted}$$

$$= 190.4 \times 10^6 - 42.1 \times 10^6$$

$$= 148.3 \times 10^6 \text{ kg/year}$$

90 percent minimum SO_2 reduction

$$SO_2 \text{ removed} = 0.90 \times 190.4 \times 10^6$$

$$= 171.4 \times 10^6 \text{ kg/year}$$

SO2 Control

- In order to follow the SO2 emission standards you consider the following possibilities:
  - Burning low sulfur fossil fuel, but this is more expensive and may not be available.
  - Reducing sulfur content of the fuel before the combustion using chemical processes, but this is very costly.
  - Removing SO2 from product gases

Removing SO2 from product gases

- Use of additive to the fuel for SO2 removal such as limestone $CaCO_3$ or dolomite $MgCO_3$, which react with SO_2 forming salts, it can remove 20-25% of SO_2.
- Use of fluidized-bed combustion, in fluidized bed combustion coal is mixed with CaO and combusted in the bed, the bed is fluidized by the air flowing through the bed. Produced SO_2 reacts with the lime CaO; $CaO+SO_2+1/2O_2 \rightarrow CaSO_4$

The lime can be regenerated

$CaSO_4+CO \rightarrow CaO + SO_2 + CO_2$

Flue gas scrubbing

- scrubbing the flue gases prior to the discharge from the stack, this has a good effectiveness of removal 70-90%, but many problems with corrosion and scaling.
  - Flue gas desulfurization FGD (wet scrubbing)
  - Dry scrubber

Wet & dry scrubbing

- In wet scrubbing systems the flue gas normally passes first through a fly ash removal device, either an electrostatic precipitator or a wet scrubber, and then into the SO2 absorber.
- However, in dry injection or spray drying operations, the SO2 is first reacted with the sorbent and then the flue gas passes through a particulate control device.

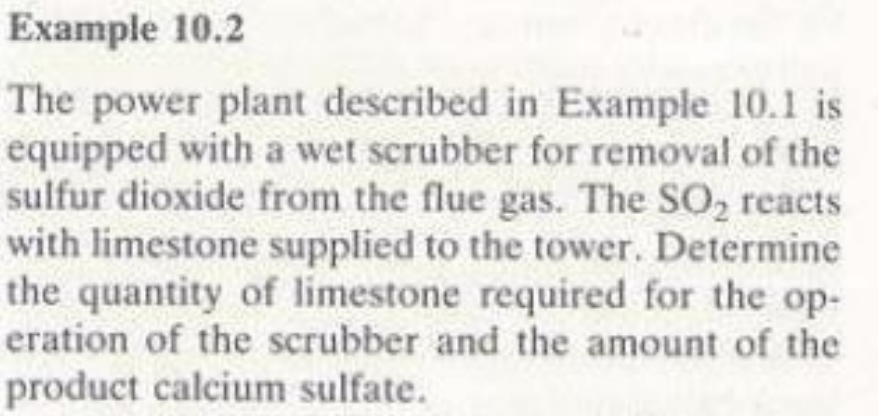
FGD - problems

- Flue gas exiting the absorber is saturated with water and still contains some SO2. (No system is 100% efficient.) Therefore, these gases are highly corrosive to any downstream equipment - i.e., fans, ducts, and stacks.
- Two methods that minimize corrosion are:
  - (1) reheating the gases to above their dew point and
  - (2) choosing construction materials and design conditions that allow equipment to withstand the corrosive conditions.

FGD

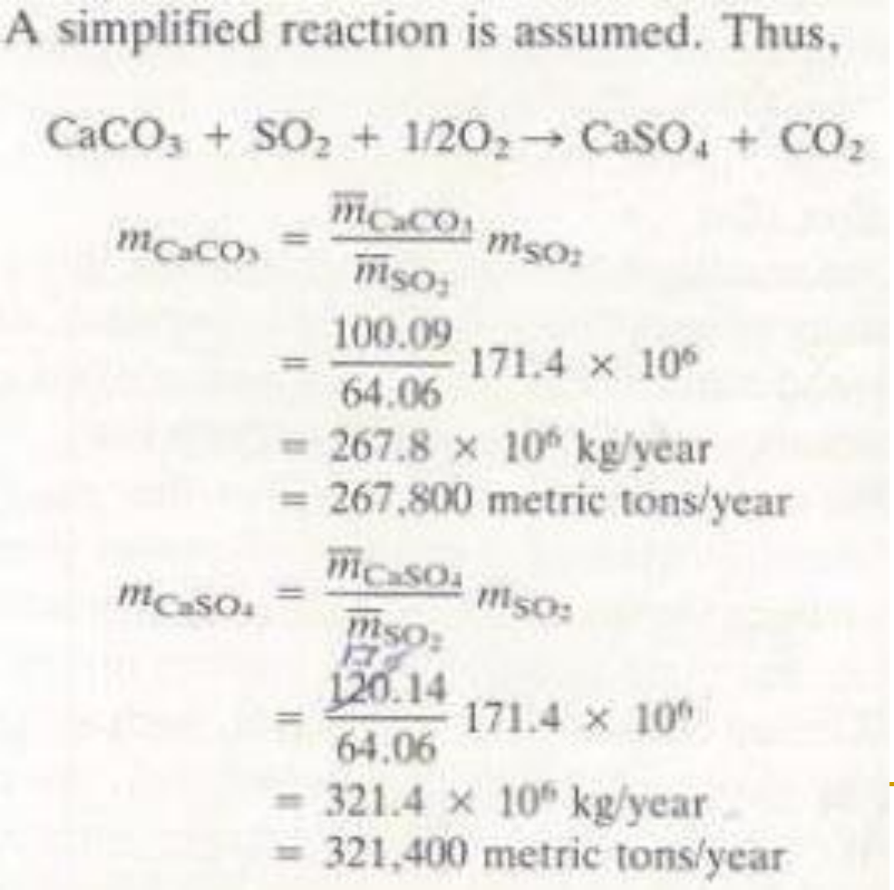
- The reaction:

  $CaCO_3 + SO_2 + (1/2)O_2 \rightarrow CaSO_4 + CO_2$
- The product $CaSO_4$ can be thrown away, or the sulfur can be regenerated and used in other sulfur industries such as producing H_2SO_4.
- *Work example 10.2 Sorenson.*



Example 10.2

The power plant described in Example 10.1 is equipped with a wet scrubber for removal of the sulfur dioxide from the flue gas. The SO_2 reacts with limestone supplied to the tower. Determine the quantity of limestone required for the operation of the scrubber and the amount of the product calcium sulfate.



A simplified reaction is assumed. Thus,

$$CaCO_3 + SO_2 + 1/2O_2 \rightarrow CaSO_4 + CO_2$$

$$\begin{aligned} m_{CaCO_3} &= \frac{\overline{m}_{CaCO_3}}{\overline{m}_{SO_2}} m_{SO_2} \\ &= \frac{100.09}{64.06} 171.4 \times 10^6 \\ &= 267.8 \times 10^6 \text{ kg/year} \\ &= 267{,}800 \text{ metric tons/year} \end{aligned}$$

$$\begin{aligned} m_{CaSO_4} &= \frac{\overline{m}_{CaSO_4}}{\overline{m}_{SO_2}} m_{SO_2} \\ &= \frac{\overset{172}{120.14}}{64.06} 171.4 \times 10^6 \\ &= 321.4 \times 10^6 \text{ kg/year} \\ &= 321{,}400 \text{ metric tons/year} \end{aligned}$$

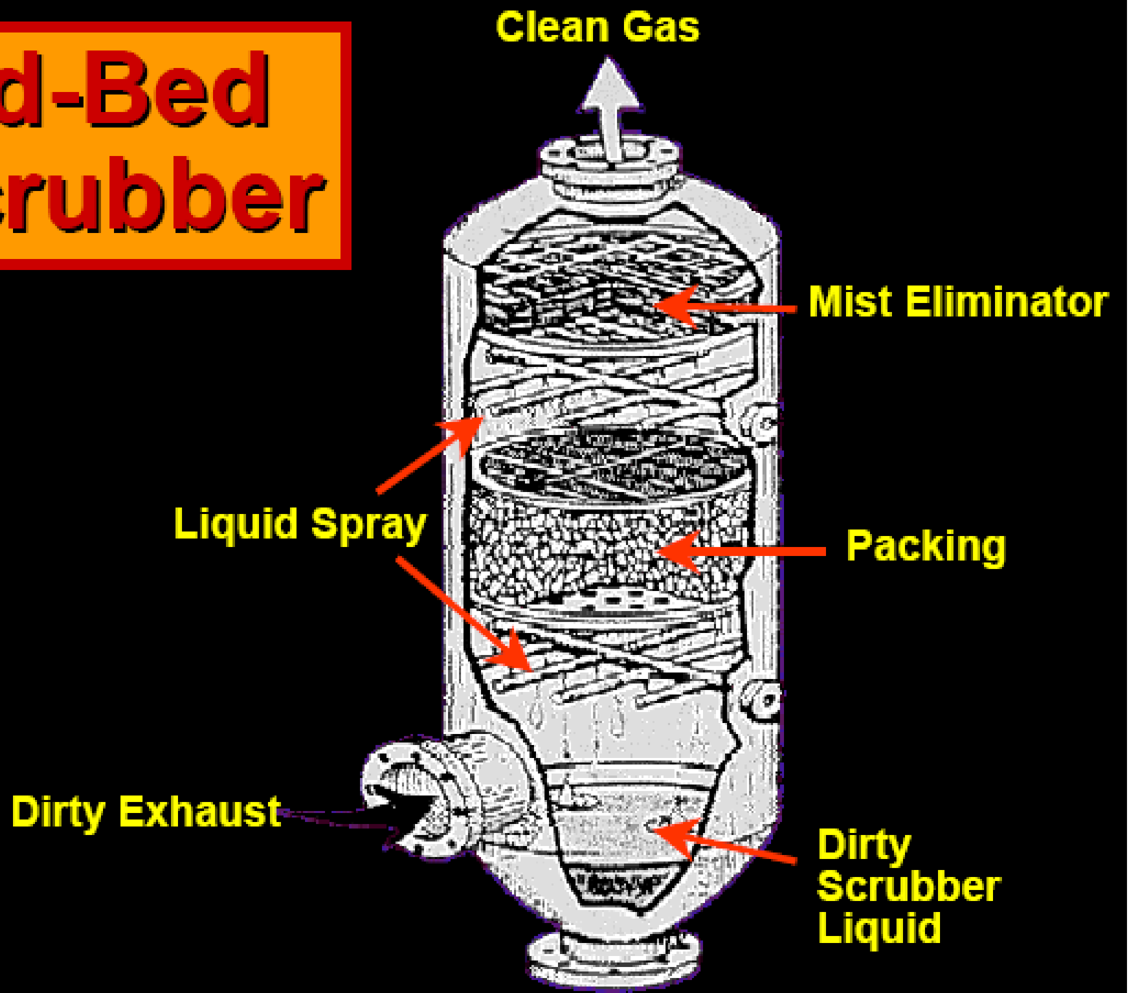
FGD equipment

- Number of wet scrubber designs have been used in wet FGD systems, including spray towers, venturis, plate towers, and mobile packed beds
- The configuration of the tower may be vertical or horizontal, and flue gas can flow concurrently, counter currently, or cross currently with respect to the liquid.

FGD

- A typical FGD system consist of 11m diameter, 22m high absorption tower, such tower is required for every 150MW.
- The tower is packed with special packing material. Water slurry of an alkali reagent such as limestone $CaCO_3$ is passed down to react with SO_2 gas, which is flowing upward the tower with the flue gases.
- Particulates are removed prior to this tower.

Packed-Bed Wet Scrubber



Dry scrubbing

- Spray dry scrubbers is the second most common method of Flue Gas Desulfurization, achieving an efficiency rating between 93-97%.
- This method uses a water based sorbent containing lime or calcium oxide that is sometimes referred to as lime milk.
- This lime slurry is atomized into a reactor vessel in the form of an extremely fine spray.
- The heat from the flue gases entering the vessel evaporates the water from the slurry and the newly hydrated lime reacts with the SO2 to form a dry mixture of calcium sulfate/sulfite.
- However, the technology is limited to the volume of flue gases produced from power plants in the 200 MW range and requires the use of the more expensive sorbent lime rather than limestone.

Dry scrubber

- Dry scrubber: is a two stages flue gas cleaning system, dry scrubber/ SO2 absorber. This system is more effective than FGD and costs less.
- 1st stage contains Ca, Na compounds introduced in a slurry into a spray dryer where SO2 reacts with Ca, Na compounds and water evaporate by thermal energy, producing a dry powder mixture of sulfate and sulfide and un-reacted alkali which are carried by flue gases into the second stage.
- 2nd stage: solid material is removed from gases using fabric filter, where additional reacting of SO2 is achieved in the fabric filter. The fabric bags also remove the particulate contained in the flue gas.

NOx Control

- NOx is formed by fixation of atmospheric nitrogen supplied by the combustion air and this known as thermal NO.
- Another source of NO comes from fuel chemically bounded nitrogen, where N might reach 2.5% of fuel by mass.
- Formation of thermal NO is influenced by many factors; the main one is the flame temperature.

Thermal NO

- Higher flame temperature produces larger amounts of NO, see table 10.1 p.359 Sorensen,
- for example at 1095 ^{o}C NO is 180 ppm: 1980^{o}C NO is 4150 ppm.
- Usually NO is formed in the furnace at temperature about the adiabatic flame temperature ≈1925 ^{o}C, when operating at atmospheric pressure.

Thermal NOx

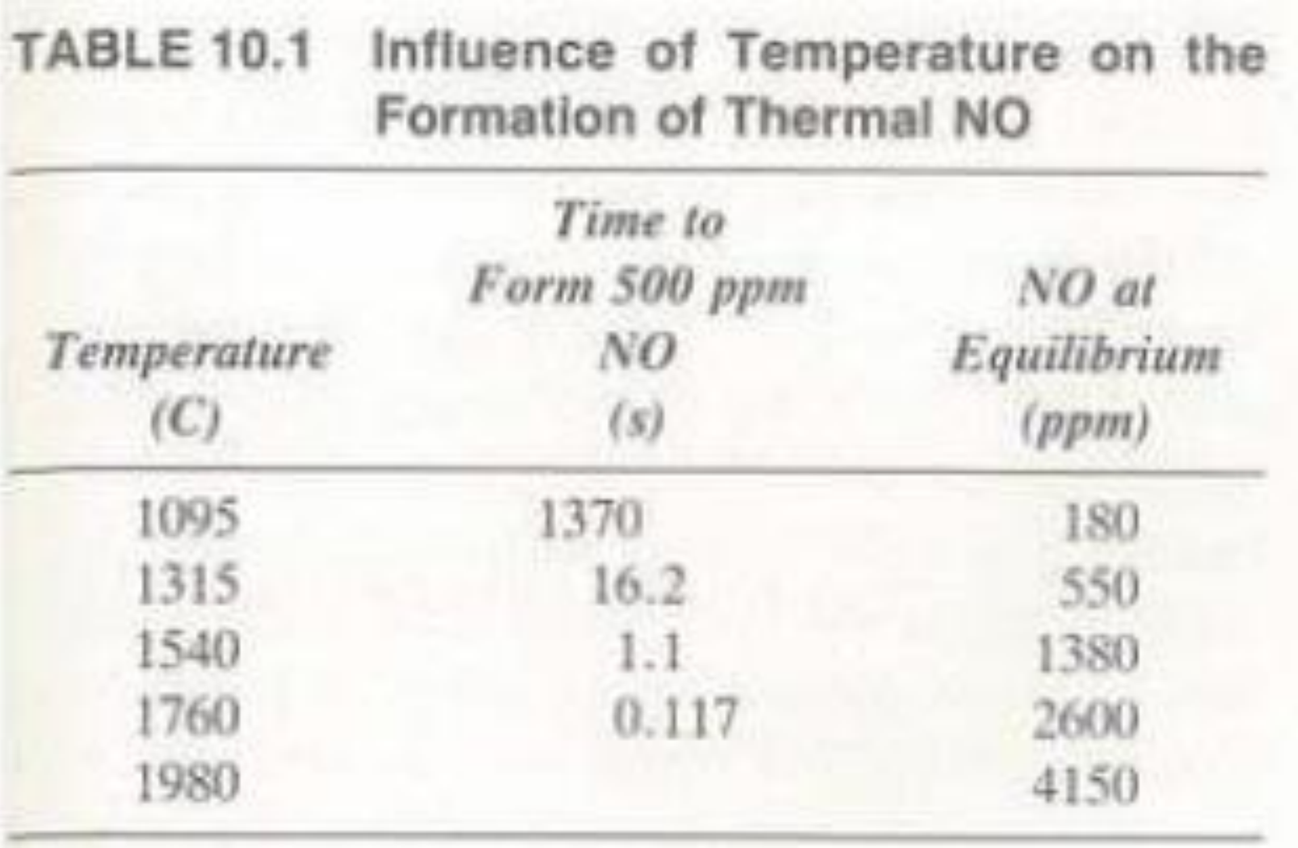


TABLE 10.1 Influence of Temperature on the Formation of Thermal NO

Temperature (C)	*Time to Form 500 ppm NO (s)*	*NO at Equilibrium (ppm)*
1095	1370	180
1315	16.2	550
1540	1.1	1380
1760	0.117	2600
1980		4150

Thermal NO

- Flame temperature is influenced by:
  - Rate of furnace cooling.
  - Combustion air temperature.
  - Excess air, since excess air reduces the temperature but increases oxygen concentration, hence enhances NO formation.

Fuel NOx

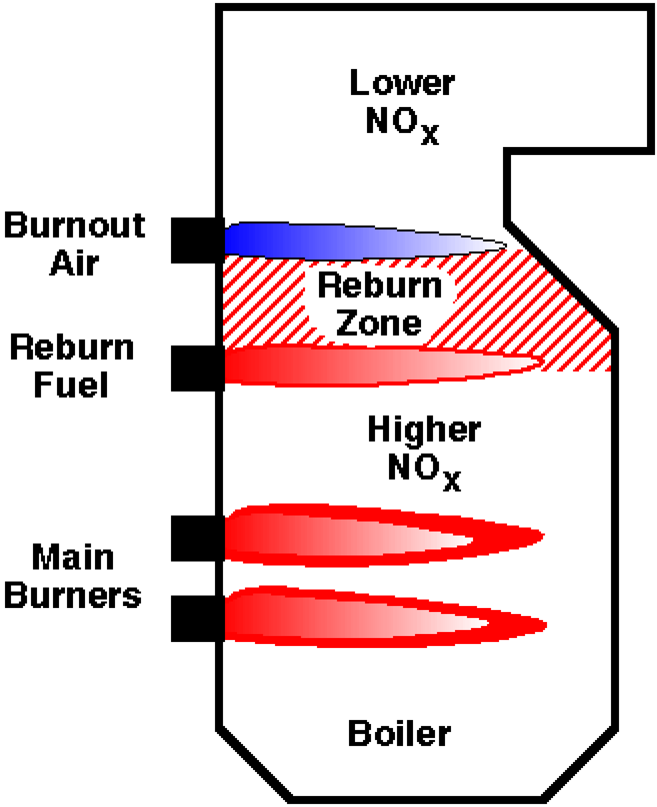
- NOx from fuel is a function of nitrogen in the fuel.
- It is found that for nitrogen 0.2-1.0% of fuel the conversion to NOx is constant and can be assumed as 21% of N.

NOx control

- Control of NOx is effectively achieved by temperature regulation in the furnace, which can be done by:
  - Flue gas recycling.
  - Two stage combustion and off stoichiometric firing
  - Increasing the cooling rate.
- Techniques such as low-excess air firing, staged combustion, flue gas recirculation, low NOx burners, and re-burning.
-

Reburning

- Reburning is accomplished by diverting a portion of a boiler's fuel, typically 10-20%, to a point above the primary combustion zone where it is injected to create a fuel rich "reburn zone.“
- The remaining combustion air is then injected above the reburn zone to provide the necessary burnout air.



Reburning

- In reburning up to 20% of the total fuel heat input is provided by injecting a secondary (or reburning)
- fuel above the main combustion zone to produce a slightly fuel-rich reburn zone with a stoichiometry of 90% theoretical air.

off- stoichiometric firing

- In off- stoichiometric firing: some of burners are operated fuel rich while the remainder are air rich, in order to obtain the required air/ fuel ratio for complete combustion,
- such firing method reduces NOx by a factor of 5-6.

two-stage combustion

- In two-stage combustion, some burners operate with fuel rich mixture (low in oxygen), this results in an incomplete combustion and lower combustion temperature.
- Additional air is admitted through oven fire air ports at a point where flame temperature is lower, and an overall air/ fuel ratio is achieved for a complete combustion.

Particulate

- Particulate emitted from power plants can cause respiratory problems and eye irritation as well as enhances smog formation.
- Smog: NO2 + Particulates + photochemical oxidation + sun light.
- Approximate size ranges of the various types of air pollutants are given below:

Particulates size

- Dust: solid particles of relatively large size = 100μm in a diameter e.g. material being handled such as coal, ash, cement.
- Fume: solid particles with diameter 0.03-0.3 μm formed by the condensation of vapors e.g. metallic oxide.
- Mist: liquid particle formed by condensation of vapor with size of 0.5-3.0 μm in diameter.
- Smoke: solid particles formed as a result of incomplete combustion of carbonaceous material, with diameter of 0.05-1 μm.
- Spray: liquid particle formed by the atomization of liquid with size 10-1000 μm in diameter.

Particulates control

- Particulates can be removed using:
    - Electrostatic precipitators.
    - Bag filters.
    - Scrubbers.
    - Mechanical dust collection.

Mechanical dust collection.

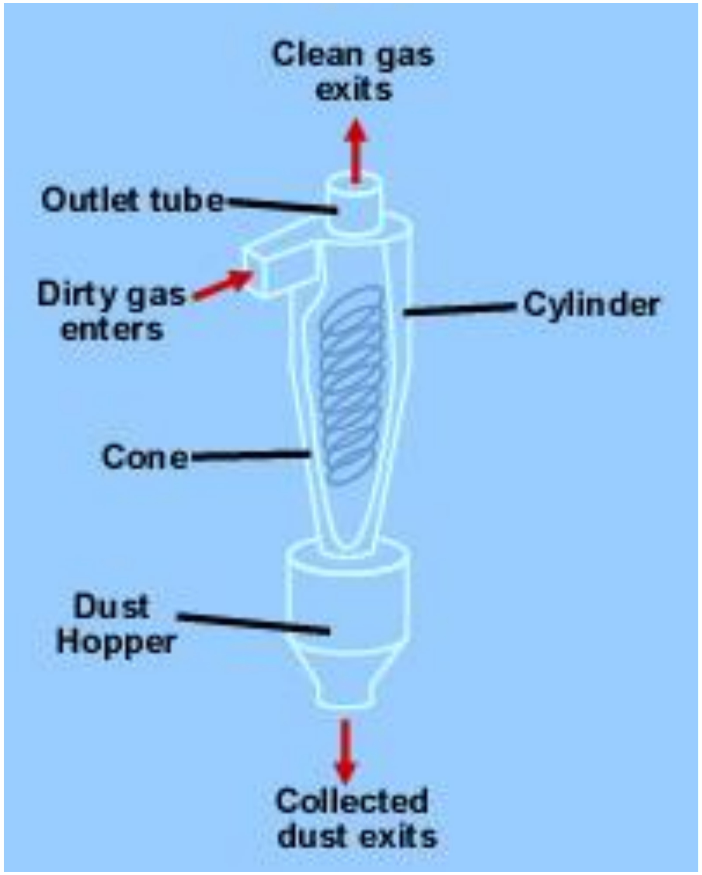
- Simplest method of particulate removal.
- It works on the principle of gravitation collection.
- Particles are trapped as they flow through various passage.
- Example of mechanical devices is the cyclone.
- Such devises are not efficient and effective for particulate removal.

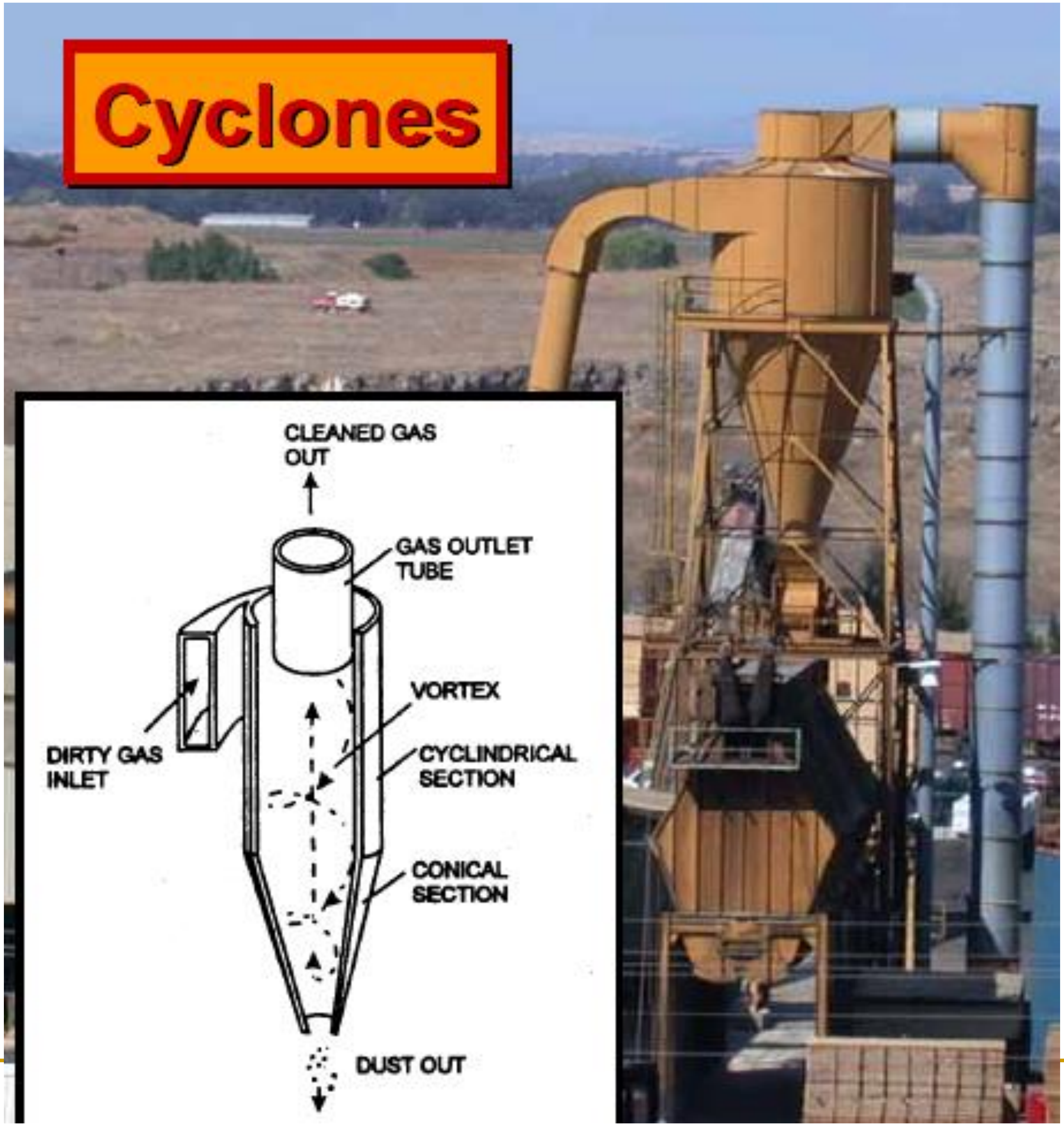
Cyclones

- Cyclones are widely used to remove coarse particles.
- They exploit the inertia of particles to separate them from air.
- As gas changes direction, the inertia of the particles causes them to continue in the original direction and be separated from the gas stream.
- Relative to gravity settlers, cyclones achieve much better collection efficiency for small coarse particles.
- Cyclones are often used upstream of fine particle control devices, such as electrostatic precipitator or fabric filter.

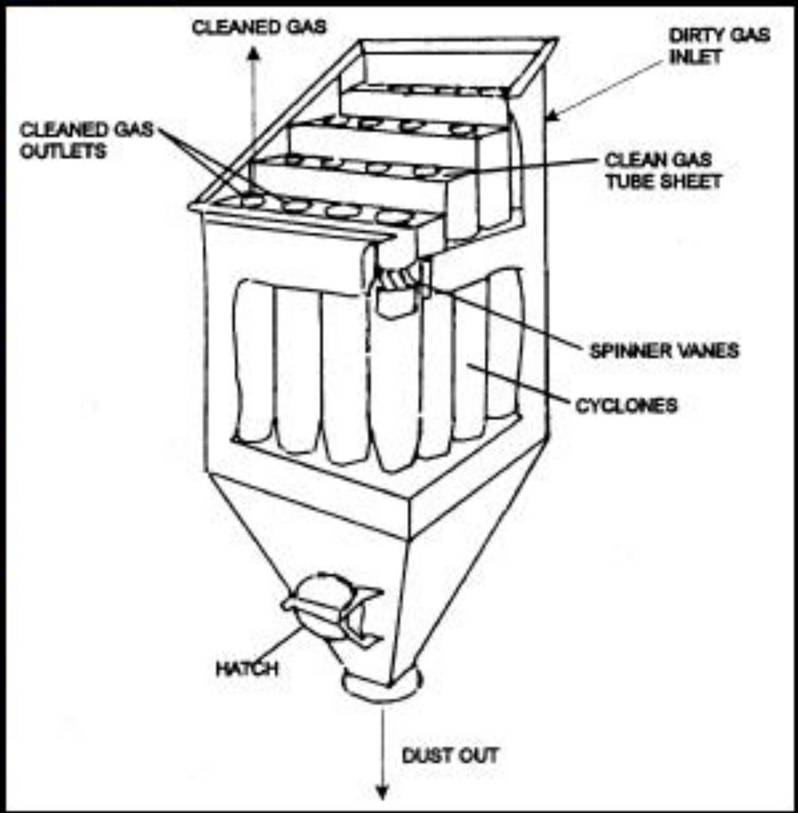
Cyclones

- Advantages of cyclones include
  - simple design and maintenance,
  - small floor area requirement,
  - low and moderate pressure drop and
  - ability to handle high particle loading rates.
-



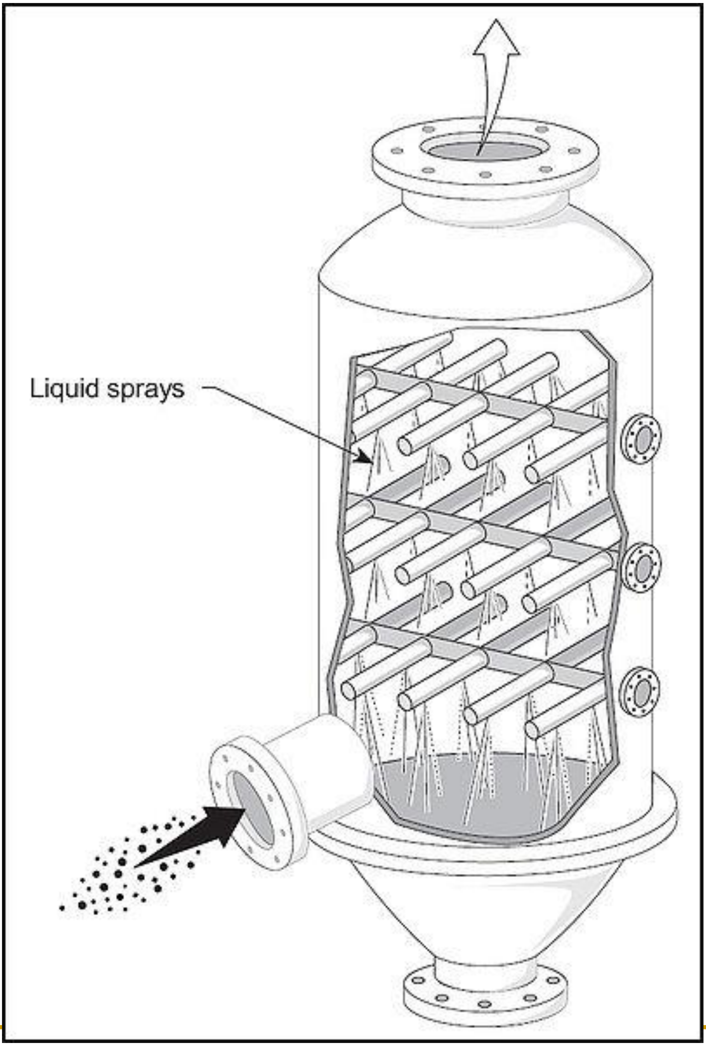

Cyclones
CLEANED GAS OUT
GAS OUTLET TUBE
VORTEX
DIRTY GAS INLET
CYCLINDRICAL SECTION
CONICAL SECTION
DUST OUT

Multi-Cyclone



Wet scrubber

- Wet scrubbers literally wash dust and particles out of the air.
- Exhaust air is forced into a spray chamber, where fine water particles cause the dust to drop from the air stream.
- The dust-laden water is then treated to remove the solid material and is often recirculated .



ELECTROSTATIC PRECIPITATORS

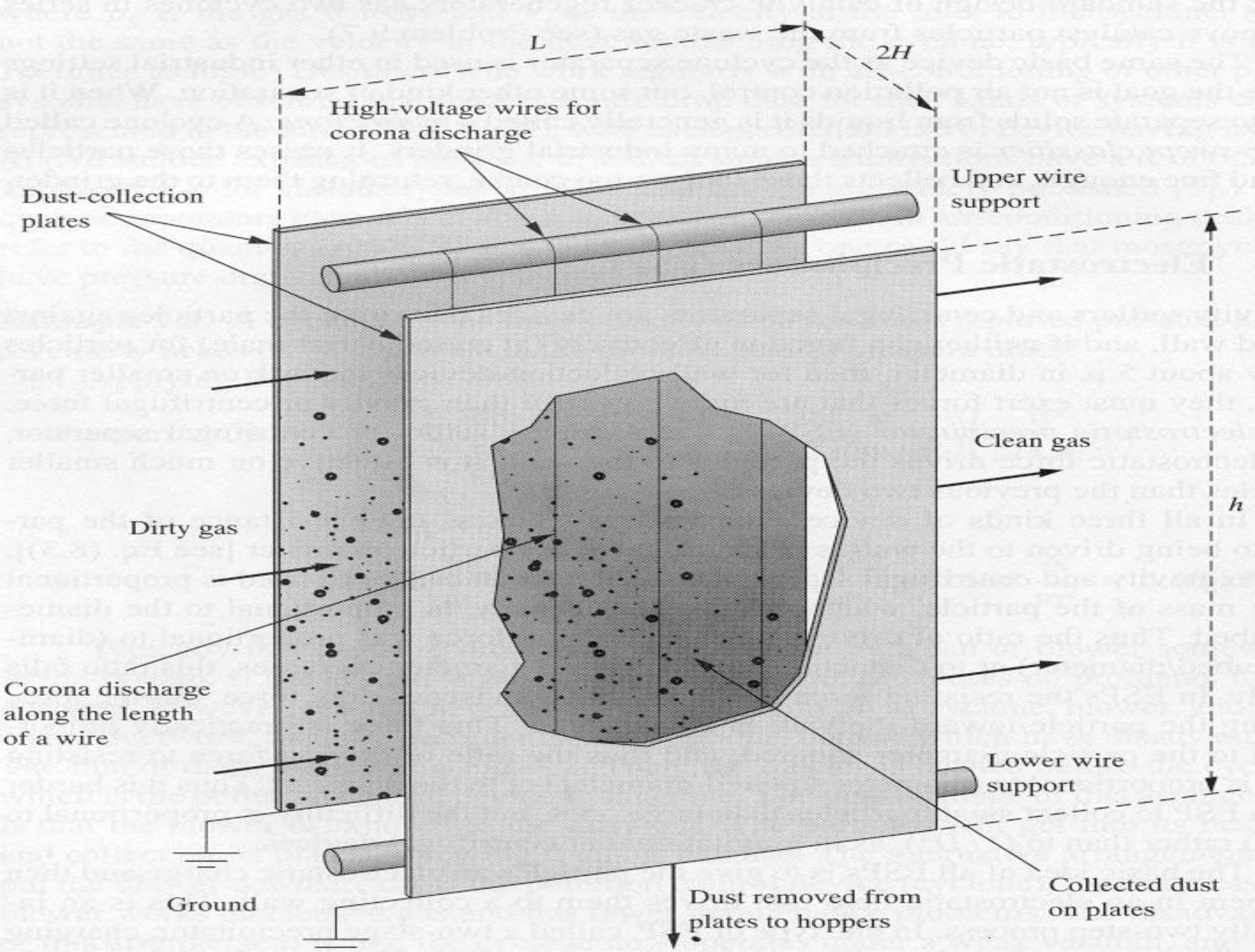


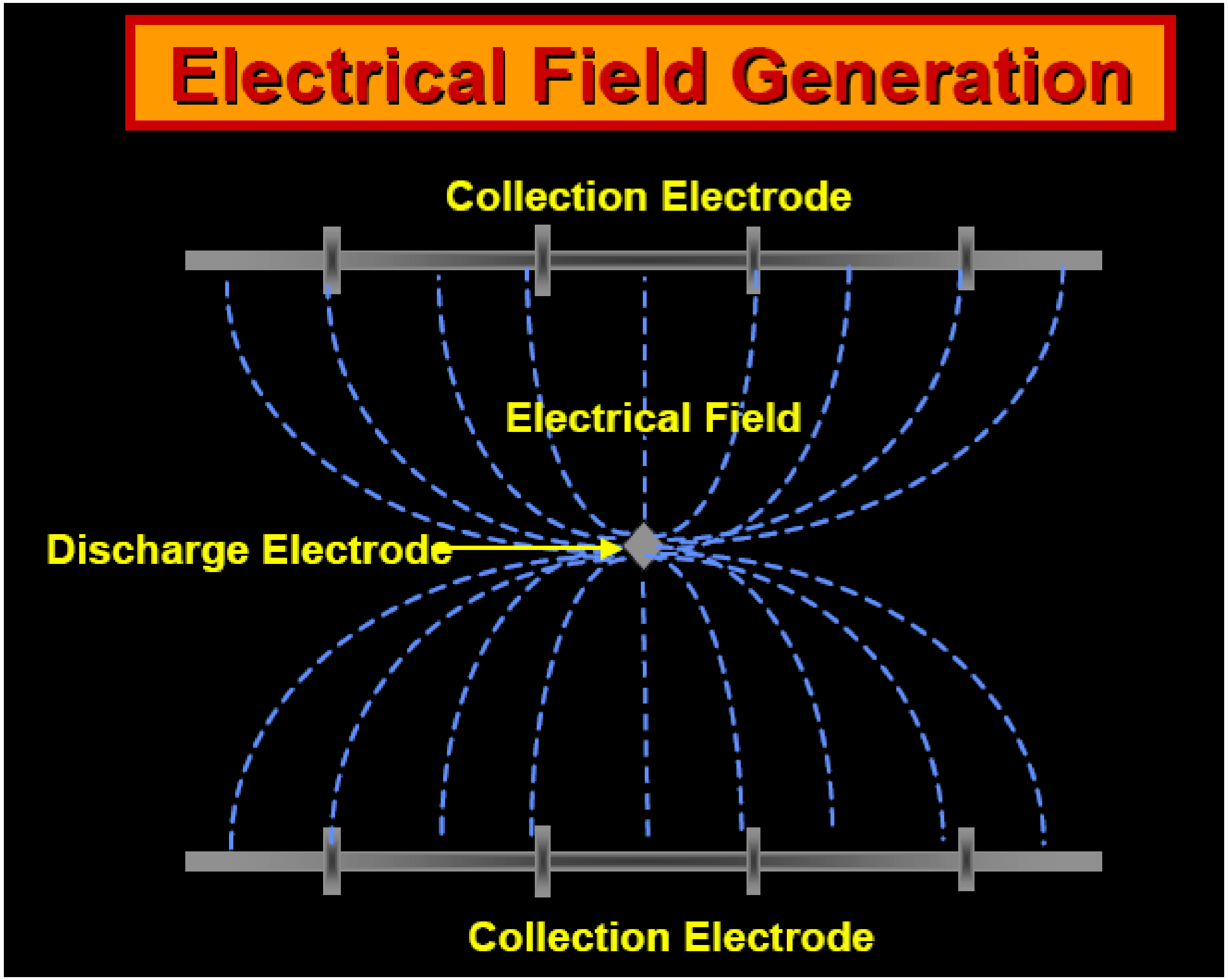
FIGURE 9.7
Diagrammatic sketch of a simplified ESP with two plates, four wires, and one flow channel. Industrial-size ESPs have many such channels in parallel; see Fig. 9.8.

EPS principles

- a particulate collection device that removes particles from a flowing gas (such as air) using the force of an induced electrostatic charge
- The most basic precipitator contains a row of thin vertical wires, and followed by a stack of large flat metal plates oriented vertically, with the plates typically spaced about 1 cm to 18 cm apart .
-

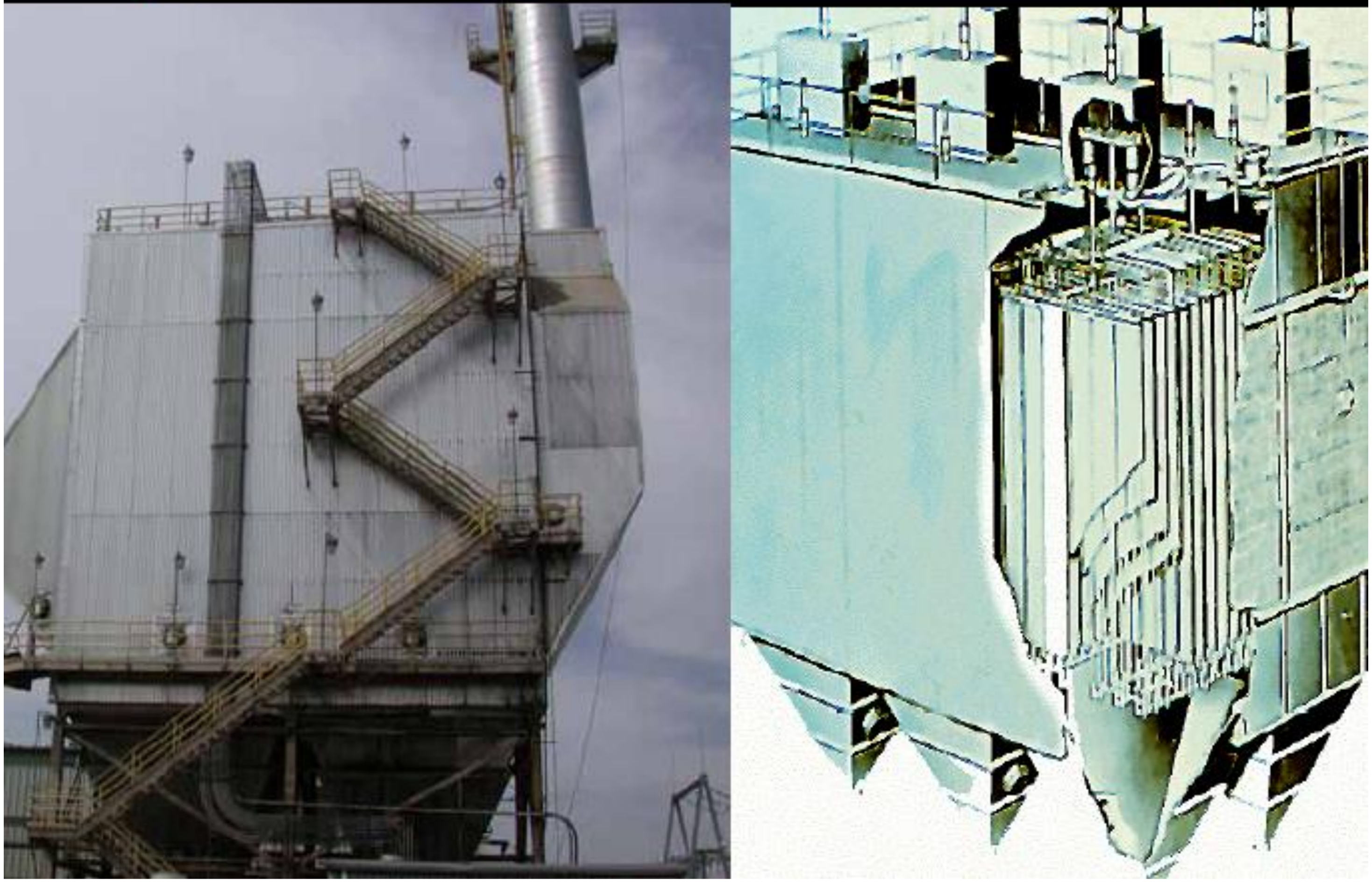
EPS

- A negative voltage of several thousand volts is applied between wire and plate. If the applied voltage is high enough an electric (corona) discharge ionizes the gas around the electrodes. Negative ions flow to the plates and charge the gas-flow particles.
- The ionized particles, following the negative electric field created by the power supply, move to the grounded plates.



Electrical Field Generation

Electrostatic Precipitator



bag filter

- bag filter becomes the best choice if following are dominant selection criteria as:
    - Material is expensive and hence high collection efficiency is desired.
    - Particulate size is very fine.
-

Working Principle of Bag Filter

- The dust-laden air enters the bag filter.
- The dust /powder separates inside the bag filter chamber.
- Initially a coat of material forms on the bags. Subsequently, the coat acts as the filtering medium.
- The dust is accumulated on filter elements while the air passes through the filter bags from outside to inside.
- The accumulated powder is dislodged from the bags by reverse pulsejet air intermittently.
- The dislodged powder falls on bottom cone and is discharged through powder discharge valves.
- The dust free air is sucked by induced draft fan and is exhausted to atmosphere.

Pulse Jet Baghouse

Thermal Pollution

- Heat rejected from power plants amounts to about 60% of fuel energy, heat rejection is a necessity of the second law of thermodynamics.
- The heat rejected is measured by a thermal discharge index TDI, which is defined as:

$$\mathrm{TDI} = \frac{(\text{thermal power discharged to environment, } \mathrm{MW_{th}})}{(\text{electrical power output, } \mathrm{MW_e})}$$

Thermal Pollution

- If Pe: electrical power output, then thermal power input in fuel is (Pe / ηth), the discharge power to environment equals:

$$(P_e / \eta_{th}) - P_e = (P_e / \eta_{th})\,(1 - \eta_{th})$$

$$TDI = (P_e / \eta_{th})\,(1 - \eta_{th})/P_e = (1 - \eta_{th}) / \eta_{th}$$

- Fossil fuel system ηth = 40% then: TDI = 1.5 which means 1.5 MWh is discharged to environment for each 1MWhelec generated.
- For light water nuclear reactor, ηth = 33% then the TDI is 2.

Energy discahrge

- In fossil fuel fired power plants, some thermal energy is discharged with stack gases and the rest by the condenser cooling system, small fraction as heat losses through out the steam generating power plant cycle.
- In gas turbine all thermal energy is discharged with the exhaust gases.
- In a nuclear power plant all thermal energy is discharged from the condenser of the steam power plant.
- The largest thermal pollution is concerned with the condenser cooling system.

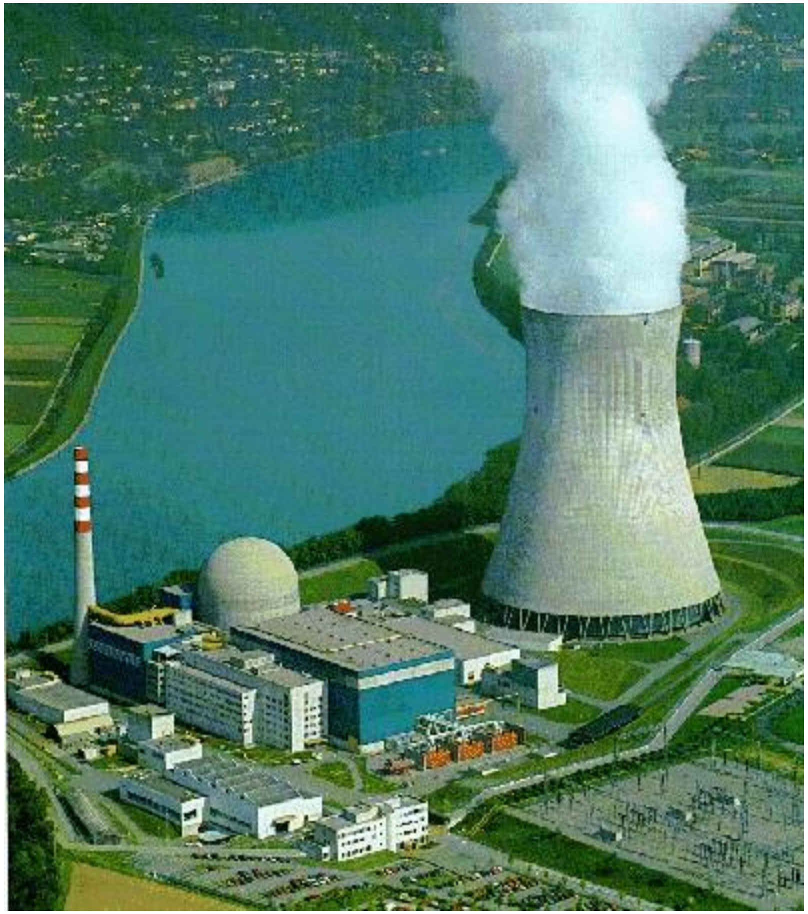
Effect of Thermal Pollution

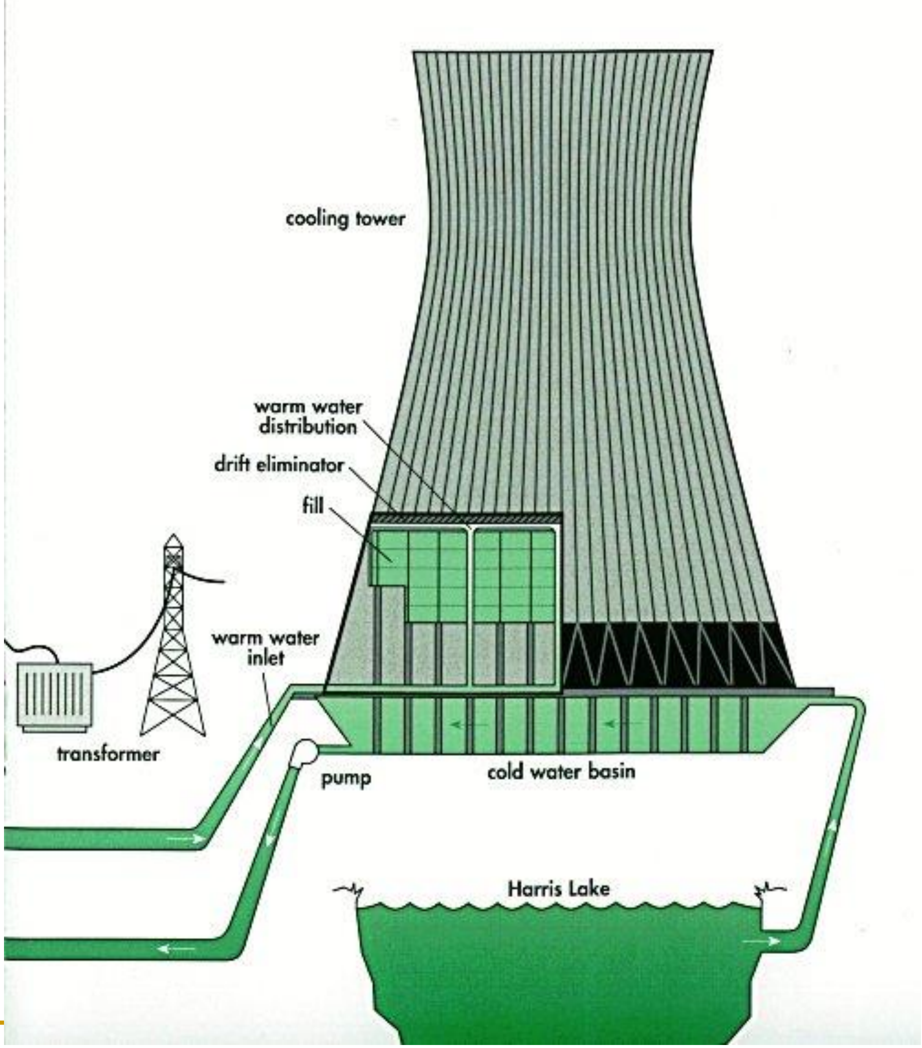
- Early steam power plants are cooled by once through cooling system. In this system water from rivers, lakes or sea is used for cooling. A temperature rise of 5 – 8 ^{o}C is anticipated for much cooling system.
- Increasing temperature of water decreases the dissolved oxygen content of the water to a degree where aquatic life is not possible, on the other hand raising the temperature enhances the growth of marine life.
- Warmer water also causes aquatic organisms to increase their respiration rates and consume oxygen faster, and it increases their susceptibility to disease, parasites, and toxic chemicals

Standards

- Limitation on the temperature rise for once-through cooling system being imposed
- for example EPA allowed a maximum of 5 ^{o}F (2.8 ^{o}C) increase in temperature.
- Other methods of cooling have to be used. Various types of cooling towers replaces the once through cooling method.

Cooling towers





Cooling towers

- Force draft towers

Nuclear pollution is not required in the final exam

Nuclear reactors

- Nuclear reactors creates several types of radiation;
  - the main types are fission fragments,
  - neutrons,
  - alpha and
  - beta particles and
  - gamma rays.
- Proper shielding against this radiation is needed in the reactor.
  - The short range alpha particles cannot penetrate the skin, but harmful if ingested within the body.
  - Alpha particles have low penetration ability and are caught within reactor structure.
  - The same applies to the large fission products which are arrested in the fuel elements.

Nuclear reactors

- Beta particles have arranged of 2.6cm in water and about 0.33cm in lead, those are usually caught in the coolant.
- Almost 10% of reactor power is in the form of gamma and neutron radiation.
- A steel thermal shield is placed just inside the reactor vessel to reduce energy level of the emitted radiation.
- A heavy external shield is required for absorbing the highly penetrating γ-rays and neutron radiation, this shield is usually built of concrete of 3m thickness.

Reactor fueling

- At the end of the operating cycle, the fuel in some of the assemblies is "spent" and is discharged and replaced with new (fresh) fuel assemblies
- buildup of reaction poisons in nuclear fuel that determines the lifetime of nuclear fuel in a reactor.
- the buildup of long-lived neutron absorbing fission byproducts impedes the chain reaction
- The fraction of the reactor's fuel core replaced during refueling is typically one-fourth for a boiling-water reactor and one-third for a pressurized-water reactor.

Nuclear fuel cycle

- Radioactive wastes occur at all stages of the nuclear fuel cycle - the process of producing electricity from nuclear materials.
- The fuel cycle comprises the mining and milling of the uranium ore,
- its processing and fabrication into nuclear fuel,
- its use in the reactor,
- the treatment of the used fuel taken from the reactor after use and finally,
- disposal of the wastes.

Nuclear waste

- Radioactive waste typically comprises a number of radioisotopes: unstable configurations of elements that decay, emitting ionizing radiation which can be harmful to human health and to the environment.
- Those isotopes emit different types and levels of radiation, which last for different periods of time.
- This nuclear waste is highly radioactive and its toxicity presents a danger for thousands of years.

Fission products

Medium-lived fission products

Prop:	**t½**	**Yield**	**Q ***	**βγ**
Unit:	**a**	**%**	**KeV**	*****
^{155}Eu	4.76	.0803	252	βγ
^{85}Kr	10.76	.2180	687	βγ
^{113m}Cd	14.1	.0008	316	β
^{90}Sr	28.9	4.505	2826	**β**
^{137}Cs	30.23	6.337	1176	β**γ**
^{121m}Sn	43.9	.00005	390	βγ
^{151}Sm	90	.5314	77	β

Long-lived fission products

Prop:	**t½**	**Yield**	**Q ***	**βγ**
Unit:	**Ma**	**%**	**KeV**	*****
^{99}Tc	0.211	6.1385	294	β
^{126}Sn	0.230	0.1084	4050	β**γ**
^{79}Se	0.295	0.0447	151	β
^{93}Zr	1.53	5.4575	91	βγ
^{135}Cs	2.3	6.9110	269	β
^{107}Pd	6.5	1.2499	33	β
^{129}I	15.7	0.8410	194	βγ

Nuclear waste management

- The main objective in managing and disposing or destruction of radioactive (or other) waste is to protect people and the environment.
- This means isolating, diluting, or destroying (transmutation) the waste so that the rate or concentration of any radionuclide returned to the biosphere is harmless.
- Radioactive waste comes from a number of sources:
  - The majority of waste originates from the nuclear fuel cycle and nuclear weapons reprocessing.
  - However, other sources include medical and industrial wastes.

Front end (Fuel preparation)

- The main by-product of enrichment is depleted uranium (DU), principally the U-238 isotope, with a U-235 content of ~0.3%. It is stored, either as UF_6 or as U_3O_8.
- Some is used in applications where its extremely high density makes it valuable, such as the keels of yachts, and anti-tank shells.

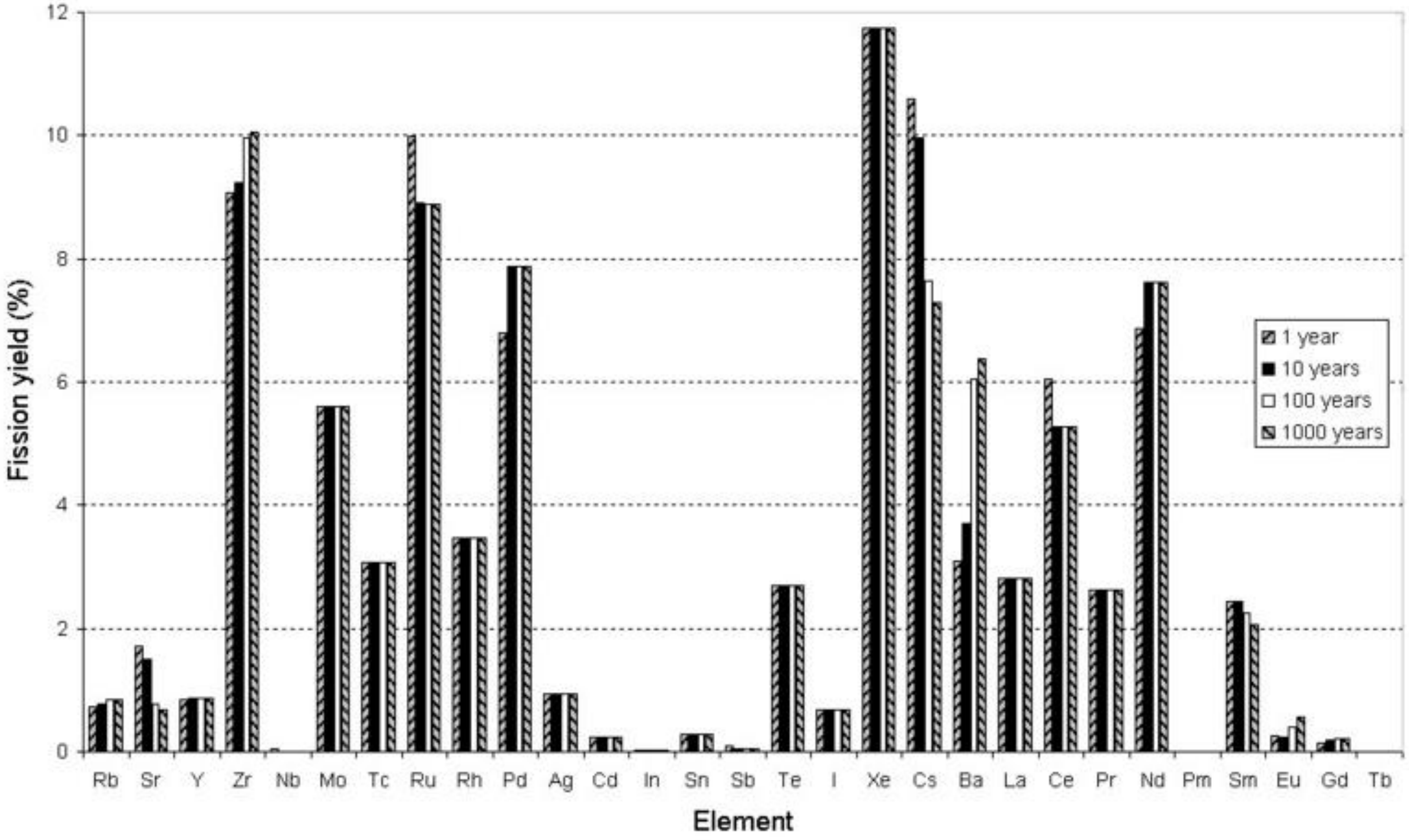
Back end

- The back end of the nuclear fuel cycle, mostly spent fuel rods, contains:
  - fission products that emit beta and gamma radiation, and
  - actinides that emit alpha particles, such as uranium-234, neptunium-237, plutonium-238 and americium-241,
  - and even sometimes some neutron emitters such as californium (Cf).
  - These isotopes are formed in nuclear reactors.

Fission products

- Sr-90 (high energy beta, half-life 30 years)
- Cs-137 (high energy gamma, half-life 30 years)
- Sn-126 (even higher energy gamma, but long half-life of 230,000 years means a slow rate of radiation release, and the yield of this nuclide per fission is very low)

Fission products

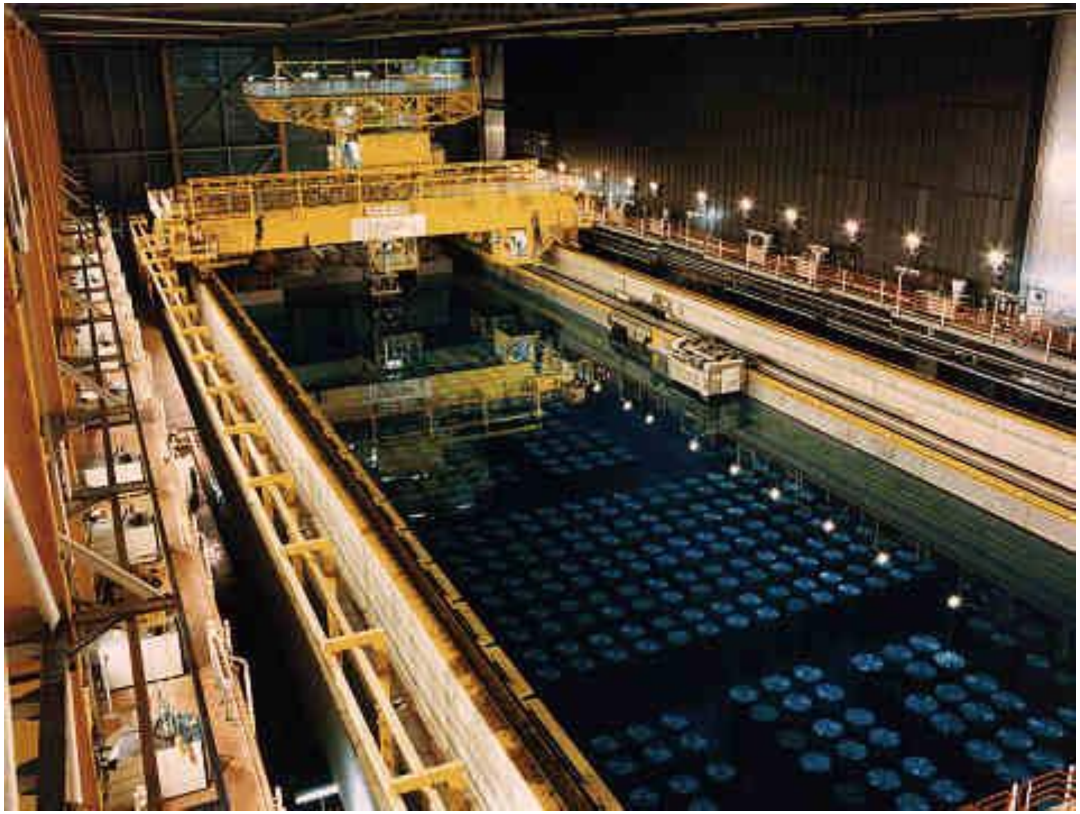


Fuel reprocessing

- About 25 tones of used fuel is taken each year from the core of a l000 MWe nuclear reactor.
- the fuel has to be replaced in the reactor with fresh fuel, even though there is still a substantial quantity of uranium-235 and plutonium present.
- In the United States, this used fuel is stored, while in countries such as the Russia,United Kingdom, France, Japan and India the fuel is reprocessed to remove the fission products, and the fuel can then be re-used.

Fuel waste

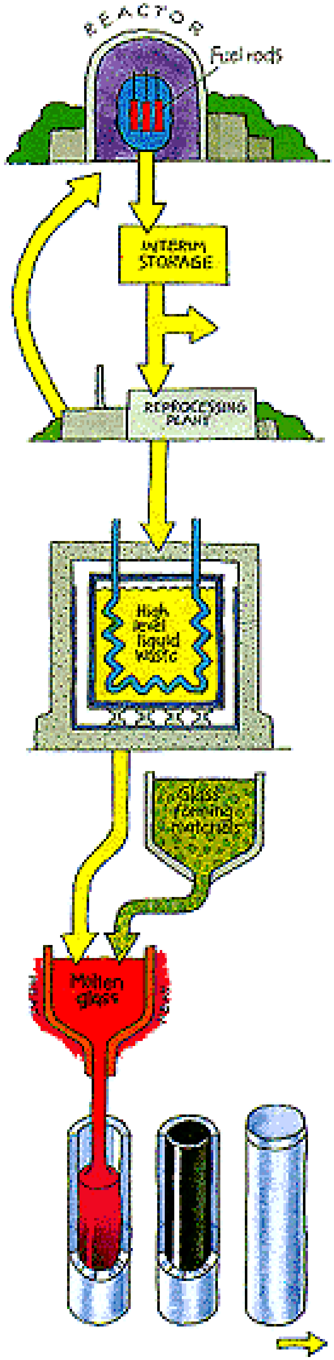
- the used fuel is first stored for several years under water in cooling ponds at the reactor site. The concrete ponds and the water covering the fuel assemblies provide radiation protection, while removing the heat generated during radioactive decay.



Fuel reprocessing

- This reprocessing involves handling highly radioactive materials, and the fission products removed from the fuel are a concentrated form of high-level waste as are the chemicals used in the process.
- Long-term storage of radioactive waste requires the stabilization of the waste into a form which will not react, nor degrade, for extended periods of time.
-

Fuel reprocessing



Vitrification

- One way to do this is through vitrification.
- the high-level waste is mixed with sugar and then calcined.
- Calcination involves passing the waste through a heated, rotating tube. The purposes of calcination are to evaporate the water from the waste, and de-nitrate the fission products to assist the stability of the glass produced.
- The 'calcine' generated is fed continuously into an induction heated furnace with fragmented glass (borosilicate glass ,similar to Pyrex), .
- The resulting glass is a new substance in which the waste products are bonded into the glass matrix when it solidifies.

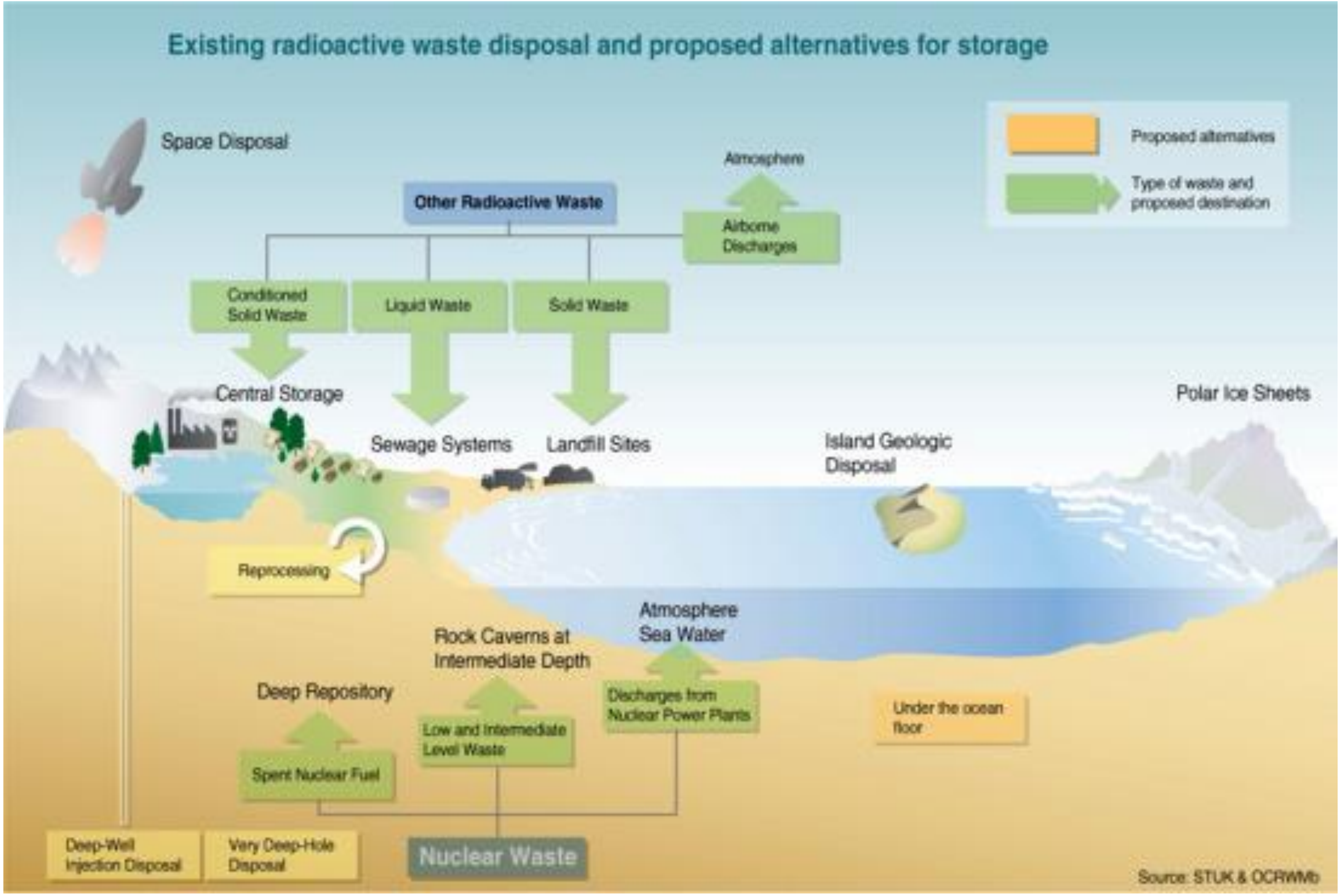
Vitrification

- This product, as a molten fluid, is poured into stainless steel cylindrical containers ("cylinders") in a batch process. When cooled, the fluid solidifies ("vitrifies") into the glass. Such glass, after being formed, is very highly resistant to water.
- After filling a cylinder, a seal is welded onto the cylinder.
- the steel cylinder is stored, usually in an underground depository .
- The vitrified waste from the operation of a 1000 MWe reactor for one year would fill about twelve canisters, each 1.3m high and 0.4m diameter and holding 400 kg of glass

Burials

- The basic concept is to locate a large, stable geologic formation and use mining technology to excavate a tunnel, or large-bore tunnel boring machines (similar to those used to drill the Chunnel from England to France) to drill a shaft 500–1,000 meters below the surface where rooms or vaults can be excavated for disposal of high-level radioactive waste.
- Sea-based options for disposal of radioactive waste include burial beneath a stable abyssal plain, burial in a subduction zone that would slowly carry the waste downward into the Earth's mantle, and burial beneath a remote natural or human-made island.

Waste disposal



Existing radioactive waste disposal and proposed alternatives for storage

Source: STUK & OCRWMb

Nuclear waste management

- Fuel elements during shutdown and fuel replacement are remotely handled.
- Adequate cooling of core even after shut down is provided to guard against high temperature developed in fuel elements.
- About one third of nuclear assembly is replaced each year.
- After cooling to low temperature in a storage (under water storage), then it is transferred to a fuel reprocessing plant.

Nuclear waste

- In reprocessing plant 99.5% of uranium and plutonium is recovered.
- High-level nuclear waste, which is very radioactive, has to be stored adequately for a long period to reach ground radiation level.
- The main high-level waste contains cesium 137 and strontium 90 with half time of 30 years.

Nuclear waste

- The waste is in the liquid form. This liquid waste is reduced to a solid, that is sealed in borosilicate glass, then is chemically inert. Solid ceramic clinkers are encased in metal tubes. These tubes are placed in a thick walled shipping cask.
- Waste materials may be stored in a salt mine, rock caverns, ice cap or deep wells drilled in the stable ocean floor.
- The nuclear waste relatively has small volume, about 2m3 for a power reactor operating at a full load for a year.

End of chapter