Welcome to

Energy Production Systems Engineering

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**Session 3:
Steam Plant
Fundamentals
& Nuclear Energy**

Spring 2012

Session 3: Steam Plant Fundamentals

- **Steam Plant Fundamentals**
- **Nuclear Energy**

Steam Plant Fundamentals

Steam Plant Fundamentals

First law of thermodynamics – energy is neither created nor destroyed, only altered in form.

Second law of thermodynamics – all thermodynamic processes are irreversible

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Steam Plant Fundamentals

Isothermal – constant temperature
Isobaric – constant pressure
Isometric – constant volume
Isentropic – constant entropy
Adiabatic – no heat transfer
Throttling – constant enthalpy

Steam Plant Fundamentals

Thermodynamic cycle:

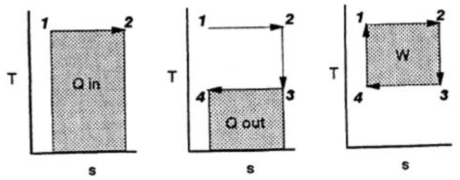
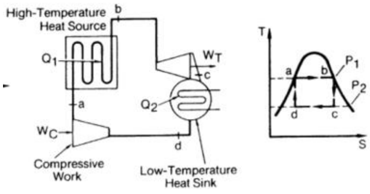


Fig. 3-7. A reversible 2T heat engine.

Steam Plant Fundamentals

Carnot Cycle (ideal) – eff = 1-(Tl/Th)

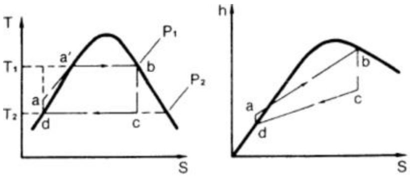


(B) Flow Device

(C) Temperature-Entropy Diagram

Steam Plant Fundamentals

Rankine Cycle –



(A) Temperature-Entropy

(B) Enthalpy-Entropy (Mollier)

Steam Plant Fundamentals

Rankine Cycle –

Q_A = Heat Added = $h_b - h_a$

Q_R = Heat Rejected = $h_c - h_d$

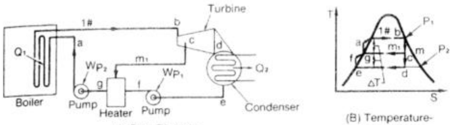
PW = Pump Work = $h_a - h_d$

W = Net Work = $h_b - h_c - PW$

η_{th} = Thermal Efficiency = $\dfrac{W}{Q_A}$

Steam Plant Fundamentals

Regenerative Design – Feedwater Heaters



(A) Flow Diagram

(B) Temperature-Entropy Diagram

W_{P_1} = Work of First Pump W_{P_2} = Work of Second Pump

FIGURE 2.1.4 Single-extraction regenerative cycle.

Steam Plant Fundamentals

Superheat Design

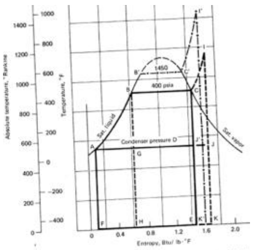


FIGURE 2.1.5 T-s diagram for superheat cycle. *Note:* (°F − 32)/1.8 = °C; (°R − 32)/1.8 = K; psia × 6.89 = kPa; Btu/(lb · °F) × 4.19 = kJ/(kg · °C). (*Westinghouse Electric Corp.*)

Steam Plant Fundamentals

Reheat Design

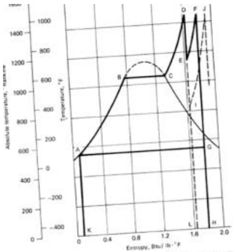


FIGURE 2.1.6 Reheat cycle. *Note:* (°F − 32)/1.8 = °C; (°R − 32)/1.8 = K; [Btu/(lb · °F)] × 4.19 = kJ/(kg · °C). (*Westinghouse Electric Corp.*)

Steam Plant Fundamentals

Condensate Depression (Subcooling) –

Process of lowering condensate Temperature below Tsat thereby reducing risk of cavitation but reducing efficiency

Increasing “Subcooling” lowers condensate temp and lowers efficiency.

Decreasing “Subcooling” raises condensate temp and increases efficiency.

Steam Plant Fundamentals

Compression/Expansion not really Isentropic

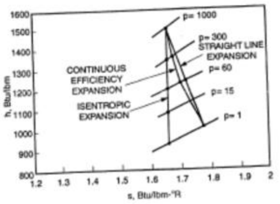


Fig. 3-23. Two turbine expansion line options (η = 0.9).

Steam Plant Fundamentals

Combined cycle – Brayton/Rankine = topping/bottoming cycle

Basic Power plant Design

Purpose: electricity / process steam
Power plant
Heating Plant
Cogeneration
Combined Cycle
Combined Cycle - Cogeneration

Basic Power plant Design

Cycle Choice – ST vs. GT
Steam vs. hot water
Fuel
Auxiliaries – duct heater
I&C
Development - DBC vs. owners engineer
Site requirements

Steam Generators

Fire Tube / Water Tube designs

FIGURE 2.3.1 General arrangement of coal-fired subcritical-pressure watertube boiler. (The Babcock & Wilcox Co.)

Steam Generators

Water Tubes hanging
from roof of boiler.

Steam Generators

Boiler Access
Door

Steam Generators

Major Components
Furnace
Steam superheater (primary & secondary)
Steam Reheater
Boiler Bank
Economizer
Steam Drum
Attemperator (temp control)

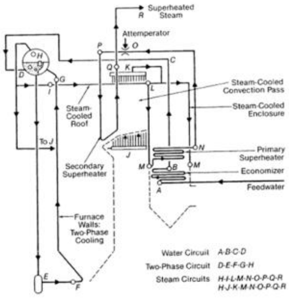
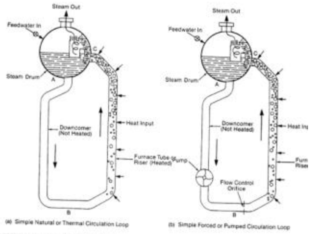


FIGURE 2.3.2 Boiler steam-water circulation system.

Water
Steam
Path

Steam Generators



(a) Simple Natural or Thermal Circulation Loop

(b) Simple Forced or Pumped Circulation Loop

FIGURE 2.3.3 Simple circulation systems.

Steam Drum
& Water
Wall
Design

Steam Generators

Combustion Air System
Natural Draft
Forced Draft
Induced Draft
Booster Fan overcome pressure drop
Air preheater
Sootblowers

Steam Generators

Water
Wall

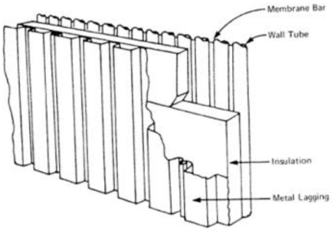


FIGURE 2.3.14 Membrane waterwall construction. (*The Babcock & Wilcox Co.*)

Steam Generators

Steam Drum
construction &
operation

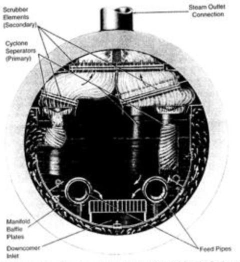


FIGURE 2.3.15 Steam drum, sectional view, showing three rows of primary cyclone separators. (*The Babcock & Wilcox Co.*)

Steam Generators

Steam
Separator

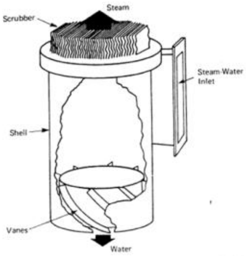
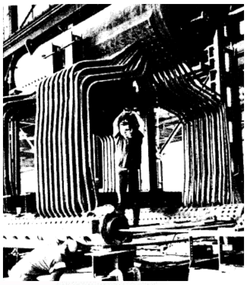


FIGURE 2.3.16 Vertical cyclone steam separator. (*The Babcock & Wilcox Co.*)

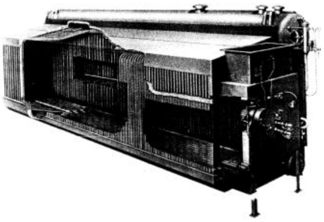
Steam Generators

A-type packaged
boilers



Steam Generators

D-type packaged
boilers



Steam Generators

O-type packaged boilers

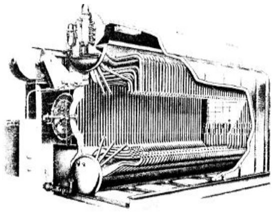


FIGURE 2.3.19 O-type packaged boiler has symmetry of design that exposes the least tube surface to radiant heat.

Steam Generators

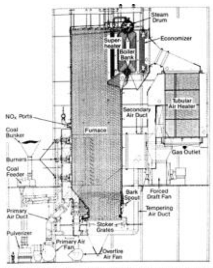


FIGURE 2.3.21 Large industrial power boiler with stoker firing and multifuel capability. (*The Babcock & Wilcox Co.*)

Field Erected units –
Stoker unit
Possible to use
Limestone in bed to
limit SO_2

Steam Generators

HRSG – Heat Recovery Steam Generator

Exhaust gas to generate steam

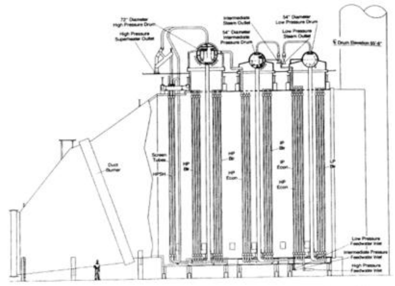


FIGURE 2.3.22 Sectional view of a multipressure heat recovery steam generator for gas-turbine exhaust applications.

Steam Generators

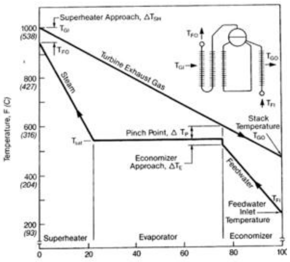


FIGURE 2.3.23 Temperature profile for a sample single-pressure HRSG.

Pinch Point &
Approach Point

Steam Generators

Fire Tube / Water Tube designs

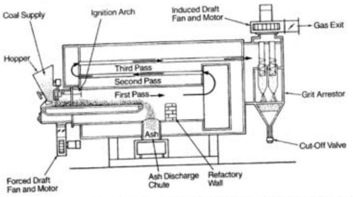


FIGURE 2.3.26 Coal-fired Scotch marine packaged firetube boiler with chain grate stoker. (*Industrial Boiler Co. NEI.*)

Steam Plant Fundamentals

Burners –
- Oxygen control – stoichiometric
- Minimize Aux energy for ignition
- Minimize NOx & SOx formation
- Collection of non combustible
- Uniform combustion
- Wide / stable firing range
- Fast response
- High availability / low maintenance

Steam Plant Fundamentals

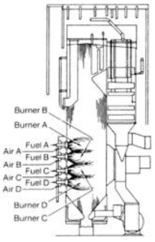


FIGURE 2.4.2 Flow pattern of horizontal (wall) firing.

Horizontally
fired burner

Steam Plant Fundamentals

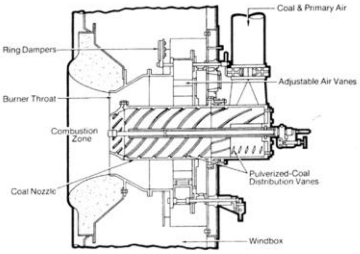


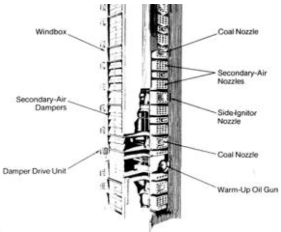
FIGURE 2.4.1 Burner for horizontal firing of coal.

Steam Plant Fundamentals

Air Dampers

Steam Plant Fundamentals

Tangentially fired burner



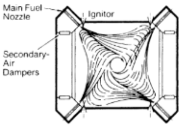


FIGURE 2.4.3 Tangential firing pattern.

Steam Plant Fundamentals

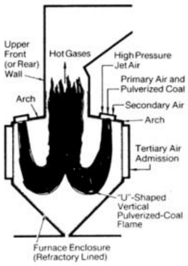


FIGURE 2.4.5 Flow pattern of vertical firing.

Vertically
fired
burner

Steam Plant Fundamentals

Cyclone
burners

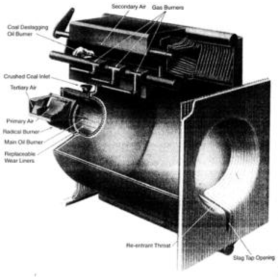


FIGURE 2.4.6 Cyclone burner.

Steam Plant Fundamentals

Low NOx burners-
NOx development dependent on Temperature when combustion takes place

Primary and secondary combustion zones – more later.

Steam Plant Fundamentals

Igniters –
Provide ignition energy
3 types of Igniters
Class1 - > 10% main burner
Class2 – 4% – 10% main burner
Class3 < 4% main burner

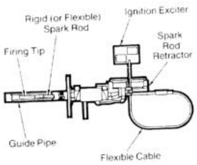


FIGURE 2.4.9 High-energy-arc igniter.

Steam Plant Fundamentals

Combustion Process –
- Adequate oxygen
- Thorough mixing of fuel & oxygen
- Temperature maintained above ignition temp
- Volume residence time adequate for complete combustion

Steam Plant Fundamentals

Stoichiometric ratio – Fuel to Oxygen

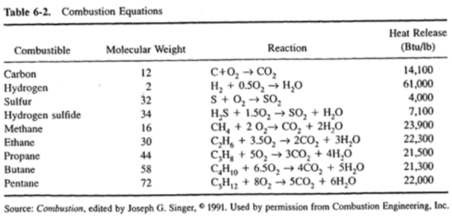


Table 6-2. Combustion Equations

Combustible	Molecular Weight	Reaction	Heat Release (Btu/lb)
Carbon	12	$C + O_2 \rightarrow CO_2$	14,100
Hydrogen	2	$H_2 + 0.5O_2 \rightarrow H_2O$	61,000
Sulfur	32	$S + O_2 \rightarrow SO_2$	4,000
Hydrogen sulfide	34	$H_2S + 1.5O_2 \rightarrow SO_2 + H_2O$	7,100
Methane	16	$CH_4 + 2\,O_2 \rightarrow CO_2 + 2H_2O$	23,900
Ethane	30	$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$	22,300
Propane	44	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	21,500
Butane	58	$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O$	21,300
Pentane	72	$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$	22,000

Source: *Combustion*, edited by Joseph G. Singer, © 1991. Used by permission from Combustion Engineering, Inc.

Steam Plant Fundamentals

Incomplete combustion –
$2\ C + O_2 \rightarrow 2\ CO$
CO is combustible with value of 4347 BTU/lbm

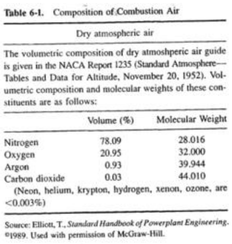


Table 6-1. Composition of Combustion Air

Dry atmospheric air

The volumetric composition of dry atmoshperic air guide is given in the NACA Report 1235 (Standard Atmosphere—Tables and Data for Altitude, November 20, 1952). Volumetric composition and molecular weights of these constituents are as follows:

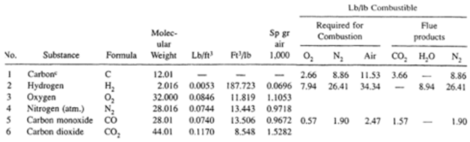
	Volume (%)	Molecular Weight
Nitrogen	78.09	28.016
Oxygen	20.95	32.000
Argon	0.93	39.944
Carbon dioxide	0.03	44.010

(Neon, helium, krypton, hydrogen, xenon, ozone, are <0.003%)

Source: Elliott, T., *Standard Handbook of Powerplant Engineering*. ©1989. Used with permission of McGraw-Hill.

Steam Plant Fundamentals

Stoichiometric air – just enough oxygen to combust fuel



							Lb/lb Combustible					
							Required for Combustion			Flue products		
No.	Substance	Formula	Molecular Weight	Lb/ft³	Ft³/lb	Sp gr air 1.000	O_2	N_2	Air	CO_2	H_2O	N_2
1	Carbon[c]	C	12.01	—	—	—	2.66	8.86	11.53	3.66	—	8.86
2	Hydrogen	H_2	2.016	0.0053	187.723	0.0696	7.94	26.41	34.34	—	8.94	26.41
3	Oxygen	O_2	32.000	0.0846	11.819	1.1053						
4	Nitrogen (atm.)	N_2	28.016	0.0744	13.443	0.9718						
5	Carbon monoxide	CO	28.01	0.0740	13.506	0.9672	0.57	1.90	2.47	1.57	—	1.90
6	Carbon dioxide	CO_2	44.01	0.1170	8.548	1.5282						

Steam Plant Fundamentals

Heat Rate – plant
NPHR = Q_B/NPO
Where;
NPHR = Net Plant Heat Rate (BTU/kWh)
Q_B = Heat into boiler (BTU/h)
NPO = Net plant output (kW)

LOWER NPHR IS BETTER!

Steam Plant Fundamentals

Heat Rate – Turbine
NTHR = Q_T/NTO
Where;
NTHR = Net Turbine Heat Rate (BTU/kWh)
Q_T = heat into turbine (BTU/h)
NTO = Net turbine output (kW)

LOWER NTHR IS BETTER!

Steam Plant Fundamentals

NPO = NTO – AP
Where
NPO = net plant output (kW)
NTO = net turbine output (kW)
AP = auxiliary power (kW)

$\eta_B = Q_T / Q_B$
Where
Q_T = heat into turbine (BTU/h)
Q_B = heat into boiler (BTU/h)

Steam Plant Fundamentals

NPHR = net plant heat rate (BTU/kWh)
NTHR = net turbine heat rate (BTU/kWh)
AP = auxiliary power (kW)
NTO = net turbine output (kW)
η_B = efficiency of boiler

$$\mathrm{NPHR} = \frac{\mathrm{NTHR}}{\eta_B\left[1 - \frac{\mathrm{AP}}{\mathrm{NTO}}\right]}$$

Steam Plant Fundamentals

To keep NPHR as small as possible ->
NTHR = small as possible
AP = as small as possible
NTO = as large as possible
η_B = as large as possible

$$\mathrm{NPHR} = \frac{\mathrm{NTHR}}{\eta_B\left[1 - \frac{\mathrm{AP}}{\mathrm{NTO}}\right]}$$

Steam Plant Fundamentals

Note η_B and NPHR are inverse of each other

A higher boiler efficiency results in lower heat rate
(this is good – less BTU for a kWh generated)

A lower boiler efficiency results in a higher heat rate
(this is not so good – more BTU for a kWh generated)

Steam Plant Fundamentals

Power plant Fans – FD, ID, PA, Gas Recirculation, Booster

Steam Plant Fundamentals

Fan operation:

Air HP = (k*V * H) / (6356*eff) where;
K = compressibility factor
V is flow (CFM)
H is head (“H_2O)
eff = mechanical efficiency

Steam Plant Fundamentals

Compressibility
Factor, K_c

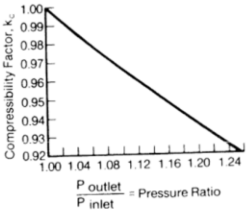
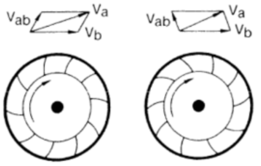


FIGURE 2.4.10 Compressibility factor for use in calculating fan power consumption, assuming adiabatic compression.

Steam Plant Fundamentals

Centrifugal fan design

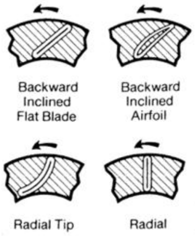


Forward Curved Backward Curved

FIGURE 2.4.11 Velocity vector diagrams comparing forward-curved and backward-curved centrifugal fan blades.

Steam Plant Fundamentals

Centrifugal fan design



Backward Inclined Flat Blade
Backward Inclined Airfoil
Radial Tip
Radial

FIGURE 2.4.12 Centrifugal (radial) fan blade types.

Steam Plant Fundamentals

Blade Type	Efficiency	Erosive Tolerance
Straight	70	High
Forward curved	80	Medium
Backward curved	85	Medium
Airfoil	90	Low

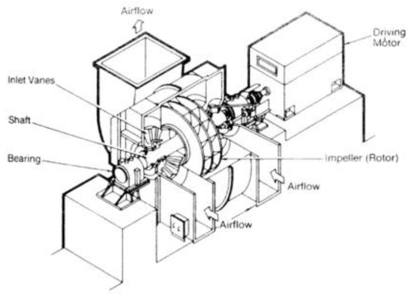


FIGURE 2.4.13 Airfoil blade centrifugal fan with inlet vane control.

Steam Plant Fundamentals

Typical fan curve

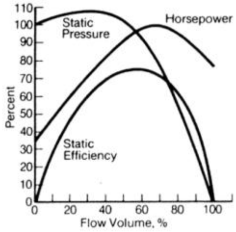


FIGURE 2.4.15 Chart showing typical constant-speed characteristics for a fan with backward-curved blades.

Steam Plant Fundamentals

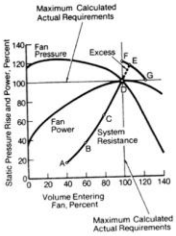


FIGURE 2.4.16 Use of characteristic curves as applied to problems of centrifugal fan selection.

Flow Control –
Damper control changes system resistance
Speed control changes fan pressure / power curve

Steam Plant Fundamentals

Axial Flow Fan

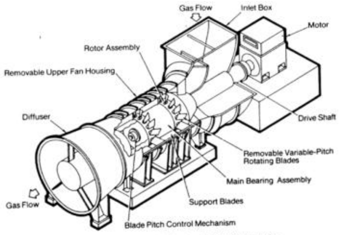


FIGURE 2.4.14 Two-stage variable-pitch axial-flow fan for induced-draft service.

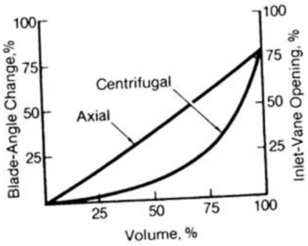


FIGURE 2.4.18 Flow control for centrifugal and axial fans.

Steam Plant Fundamentals

Axial Fan Air
Foil Blading

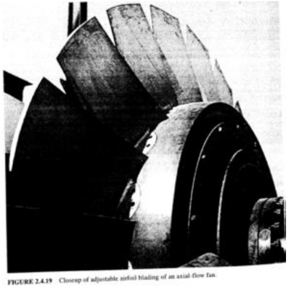


FIGURE 2.4.19 Closeup of adjustable airfoil blading of an axial-flow fan.

Steam Plant Fundamentals

Speed ctrl –
Erosion reduction
Startup shock
Flow ctrl
Noise reduction
Power draw at startup

Fluid drive, two speed motor, VSD, ST drive

Steam Plant Fundamentals

Fan fundamental law;
Power = flow * head

Steam Plant Fundamentals

Fan Laws

1. For given size, R-sys, and density;
    1. When speed varies
        1. Flow varies directly with speed
        2. Pressure varies to square of speed
        3. Power varies to cube of speed
    2. When pressure varies
        1. Flow & speed vary as sqrt
        2. Power varies by 1.5

Steam Plant Fundamentals

Fan Laws – density changes

2. For constant pressure
    1. Speed, flow, power vary as sqrt of density (directly for pressure, inverse for temperature)
3. For constant flow & speed
    1. HP and pressure vary directly to density (directly for pressure, inverse for temperature)

Steam Plant Fundamentals

Fan Laws – density changes

4. For constant flow
    1. Capacity, speed, pressure vary inversely to density
    2. Power varies inversely as square of density

Air Preheater

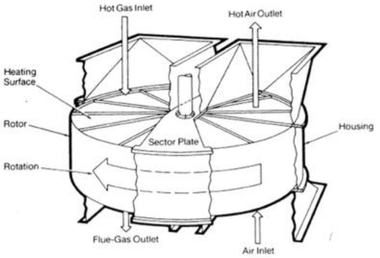
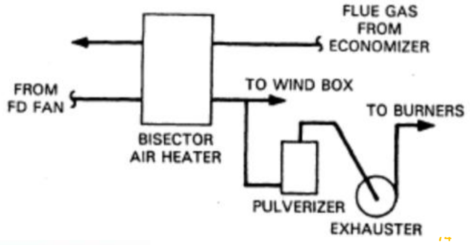
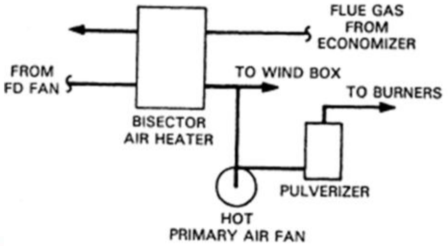


FIGURE 2.4.22 Details of regenerative air preheater, bisector type.

BISECTOR WITH EXHAUSTER MILL



BISECTOR WITH HOT PRIMARY AIR FAN AND PRESSURIZED PULVERIZER



THREE BISECTORS–SEPARATE PRIMARY AIR HEATER AND PRESSURIZED PULVERIZERS

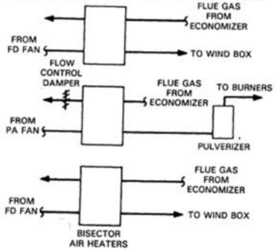
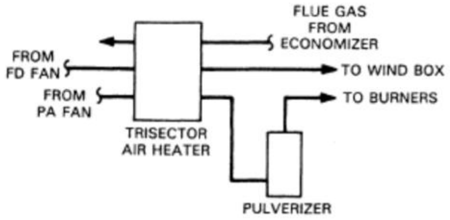


Fig. 7-10. Bisector air heater arrangements.

SINGLE TRISECTOR



Steam Plant Fundamentals

Crusher
Dryer

Steam Plant Fundamentals

Ball
Tube
Mill

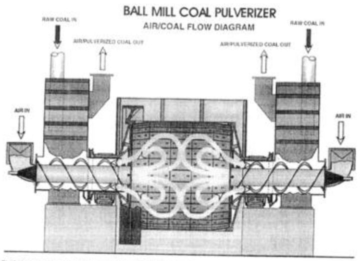


Fig. 7-20. Ball tube mill. (Illustration courtesy of Foster Wheeler Corporation.)

Steam Plant Fundamentals

Classifier

Steam Plant Fundamentals

Ball & Race
Mill

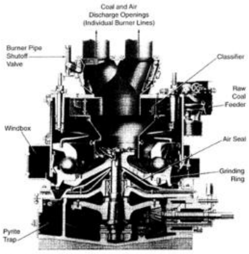


FIGURE 2.4.39 Type EL ball-and-race mill.

Steam Plant Fundamentals

Roll Ring
Mill

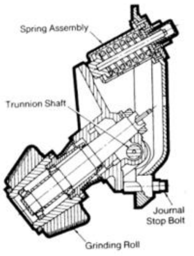


FIGURE 2.4.42 Diagram of bowl-type ring-roll mill journal.

Steam Plant Fundamentals

Roll Ring Mill

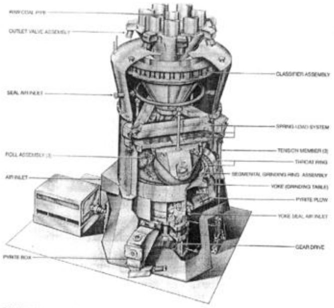


Fig. 7-22. Vertical spindle mill. (From Babcock & Wilcox. Used with permission.)

Steam Plant Fundamentals

Stokers
Underfeed

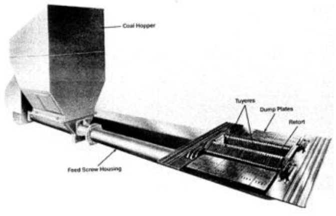


FIGURE 2.4.45 Screw conveyor feeds coal from hopper to retort.

Steam Plant Fundamentals

Stokers
Overfeed

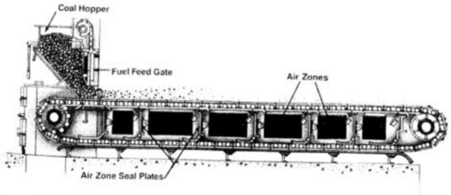
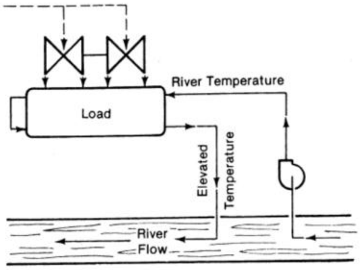


FIGURE 2.4.49 Cross section of overfeed mass-burning chain grate stoker.

Cooling Towers / Air Cooled Condensers



Cooling Towers / Air Cooled Condensers

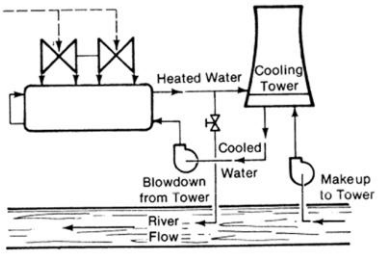


FIGURE 2.5.2 Closed-circuit system.

Cooling Towers / Air Cooled Condensers

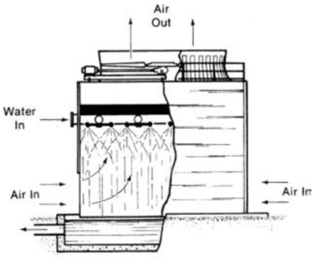


FIGURE 2.5.3 Counterflow induced-draft tower.

Steam Plant Fundamentals

Heat Balance – Heat gained by air = Heat lost by water + heat loss by evaporation.

G = Mass flow air, h = enthalpy
L = Mass flow water, T = temp
H = Humidity ratio

$$G\,\Delta h = L\,\Delta t + G\,\Delta H(t_2 - 32)$$

$$G\,\Delta h = L\,\Delta t + G\,\Delta H\,t_2 \qquad \text{(metric)}$$

Steam Plant Fundamentals

Natural draft vs. mechanical draft
Induced draft vs. Forced Draft
Cross flow verses counterflow
Splash type fill vs. film type fill

Steam Plant Fundamentals

Natural Draft Tower

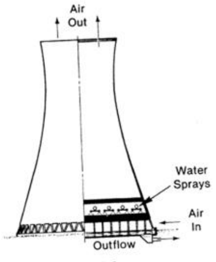


FIGURE 2.5.7 Natural-draft tower.

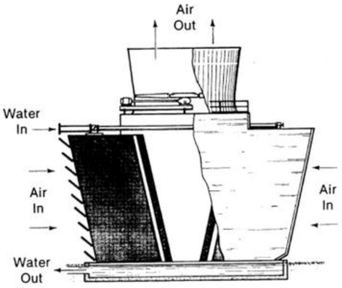


FIGURE 2.5.8 Double-flow cross-flow tower.

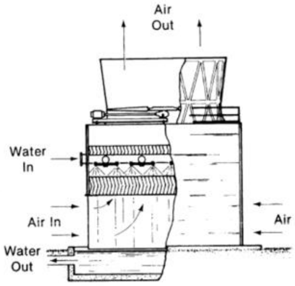


FIGURE 2.5.9 Induced-draft counterflow tower.

Steam Plant Fundamentals

Splash type fill

FIGURE 2.5.12 Splash-type fill.

Steam Plant Fundamentals

Film Type Fill

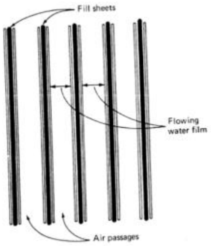


FIGURE 2.5.14 Schematic representation of film fill.

Steam Plant Fundamentals

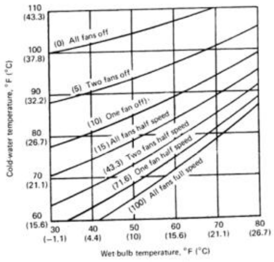


FIGURE 2.5.17 Three-cell tower with two-speed motors.

Regulate cold side
(water out) temp
by air flow control

Steam Plant Fundamentals

Air Cooled condenser –
Dry cooled (direct / indirect) Fin cooler

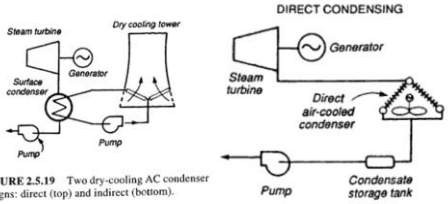


FIGURE 2.5.19 Two dry-cooling AC condenser designs: direct (top) and indirect (bottom).

Steam Plant Fundamentals

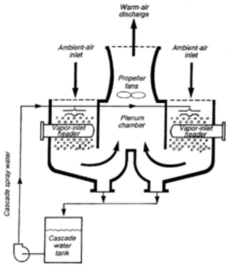


FIGURE 2.5.20 AC condenser with wet-surface cooling.

Air Cooled
condenser –
Wet surface
cooled

Water Treatment

Impurities – deposit and erode

Turbidity – insoluble matter

Hardness – calcium & magnesium deposit out

Soluble gases – accelerate corrosion

Biological - fowling

Water Treatment

Pretreatment –
  sedimentation
  clarification
  filtration
  softening
  oxidation
  degasification
  Demineralization –
    evaporation
    ion exchange
    RO

Water Treatment

Oxidation – chemical addition or aeration
Convert soluble gas to solids

Sedimentation – settle out suspended matter

Clarification – add coagulants to settle out smaller suspended matter

Water Treatment

Flocculation – after clarification slowly stir to further increase particle size and remove suspended matter

Softening – removed dissolved impurities by chemical reaction to convert to a removable form.

Water Treatment

Filtration – process of passing fluid through medium perpendicular to medium to remove solids. Follows clarification/flocculation.

Water Treatment

Demineralization –
- Ion Exchange
- Evaporation
- RO

Water Treatment

Evaporation – flash distillation

Water Treatment

Reverse Osmosis (RO) –
Uses semipermeable membrane and pressure to separate.
Results in concentrate & permeate.

Ultra filters (UF) & Micro filters (MF) alternate to RO

RO pores are smallest, MF pores are largest

Water Treatment

Ion Exchange – Uses resin beds to replace unwanted ions with less objectionable ions

End of

Steam Plant Fundamentals

Nuclear Energy

Nuclear Energy

^{235}U most common fuel
Neutron fission of U to other decay particles
Moderator – reduce neutron energy to increase fission
Coolant – remove heat from Fuel rods
Half-life – avg time for one half of population to decay

Nuclear Energy

Fissile material generates neutron and non fissile material
Fertile material generates neutron and fissile material
Breeder – generates more fuel than it consumes
Converter – generates less fuel than it consumes

Nuclear Energy

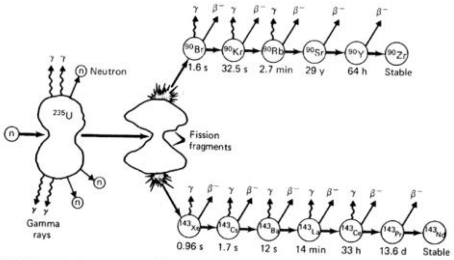


FIGURE 6.2.1 Neutron fission of ^{235}U showing two representative fission product decay chains.[10]

Nuclear Energy

$$k = \frac{\text{rate of production}}{\text{rate of absorption} + \text{rate of leakage}}$$

$$\rho = \frac{k-1}{k}$$ p = accumulation/production

K = neutron multiplication factor
P = reactivity

K = 1, p = 0 ; System is critical
K < 1, p < 0 ; System is subcritical
K > 1, p > 0 ; System is supercritical

Nuclear Energy

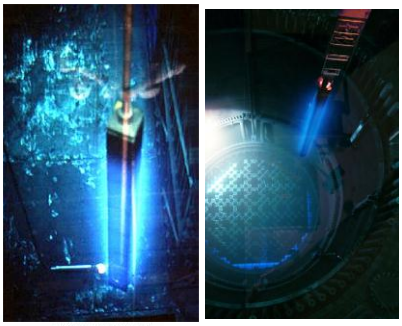
Method to control nuclear reactor –
Adjust production, leakage, absorption of neutrons
Soluble neutron poisons
Control rods
Fixed burnable poisons
Scram – insertion of control rods by gravity / gas pressure
Negative temperature feedback – increased temperature > less neutrons moderated.

Nuclear Energy

A Fuel bundle being transferred under water

Cerenkov Radiation (That blue glow).

Water used for shielding and cooling.



Nuclear Energy

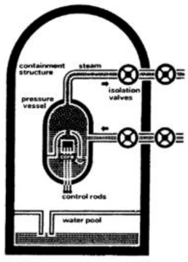
Fuel Rod Storage

Nuclear Energy

Six types of nuclear steam system (80s design)
BWR = Boiling Water Reactor
PWR = Pressurized Water Reactor
PHWR = Pressurized Heavy Water Reactor
PTGR = Pressurized Tube Graphite Reactor
HTGR = High Temperature Gas Cooled Reactor
LMFBR = Liquid Metal Fast Breeder Reactor

Nuclear Energy

Boiling water reactor



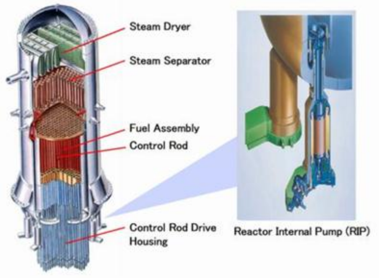
(a) Boiling-water reactor (BWR)

Nuclear Energy

BWR –
Steam generated in pressure vessel
Light water – coolant and moderator
Wet steam turbines employed
Reactivity control – Control rods & coolant flow
Bottom mounted control rods inserted via gas pressure

ABWR

Nuclear Energy



Nuclear Energy

ABWR –
Use of internal recirc pumps to eliminate external jet pumps
Finer control rod adjustment
Operation action to LOCA 3 days
ESBWR-
Natural circ. – no recirc or jet pumps
Condenser / hx to remove heat
Large Pool to flood vessel in LOCA

Nuclear Energy

To be continued …

Energy Production Systems Engineering

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**End of Session 3:
Steam Plant
Fundamentals
& Nuclear Energy**

Spring 2012