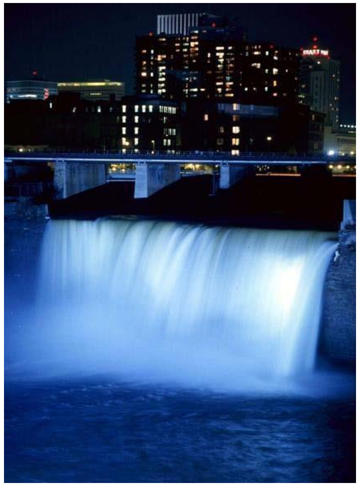
Power System Fundamentals



Generation Unit Basics

PJM State & Member Training Dept.

Objectives

- Given a generating unit, describe the basic steps involved in the energy conversion process
- Describe the overall design and function of plant systems that are common to most facilities
  - Steam/condensate/feedwater systems
  - Turbine support systems
  - Start-up Systems

Objectives

  - Circulating water/Cooling water Systems
  - Sealing systems
  - Air Systems
- Given a generating unit, list some possible Environmental limitations that may restrict unit output
- Given a generating unit, list some possible Operational limitations that may restrict unit output

Objectives

- Describe the major design elements of a Fossil Unit
- Describe the major design elements of a Nuclear Unit
- Describe the major design elements of a Hydroelectric Unit
- Describe the major design elements of a Combustion Turbine Unit

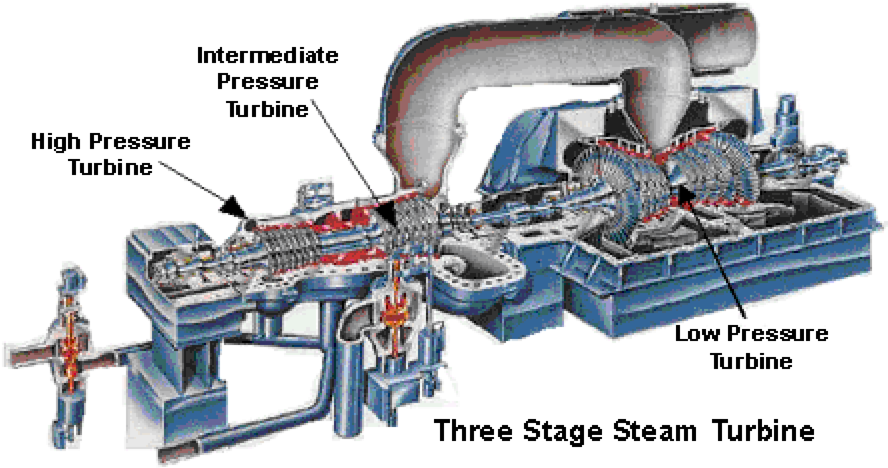
Objectives

- Describe the major design elements of a Combined Cycle Unit
- Describe the major design elements of a Wind Unit
- Describe the major design elements of a Solar Unit

Agenda

- Elements of the Energy Conversion Process
- Provide an overview of:
  - Steam/Condensate/Feedwater and other Common Systems
- Describe the various types of units:
  - Fossil generating units
  - Nuclear generating units
  - Hydroelectric generating units
  - Combustion turbines
  - Combined Cycle Power Plants (CCPP)
  - Wind Units
  - Solar Units

Generation Unit Basics



Three Stage Steam Turbine

Basic Energy Conversion

Generating Unit Principles of Operation

Fossil Conversion Process	Nuclear Conversion Process
Chemical Energy (Fuel)	Nuclear Energy (Fission)
to	to
Thermal Energy (Steam)	Thermal Energy (Steam)
to	to
Mechanical Energy (Turbine)	Mechanical Energy (Turbine)
to	to
Electrical Energy (Generator)	Electrical Energy (Generator)

Generating Unit Principles of Operation

Hydro Conversion Process	Wind Conversion Process
Kinetic Energy (Falling water)	Kinetic Energy (Wind)
to	To
Mechanical Energy (Turbine)	Mechanical Energy (Turbine)
to	to
Electrical Energy (Generator)	Electrical Energy (Generator)

Agenda

- Elements of the Energy Conversion Process
- Provide an overview of:
    - Steam/Condensate/Feedwater and other Common Systems
- Describe the various types of units:
    - Fossil generating units
    - Nuclear generating units
    - Hydroelectric generating units
    - Combustion turbines
    - Combined Cycle Power Plants (CCPP)
    - Wind Units
    - Solar Units

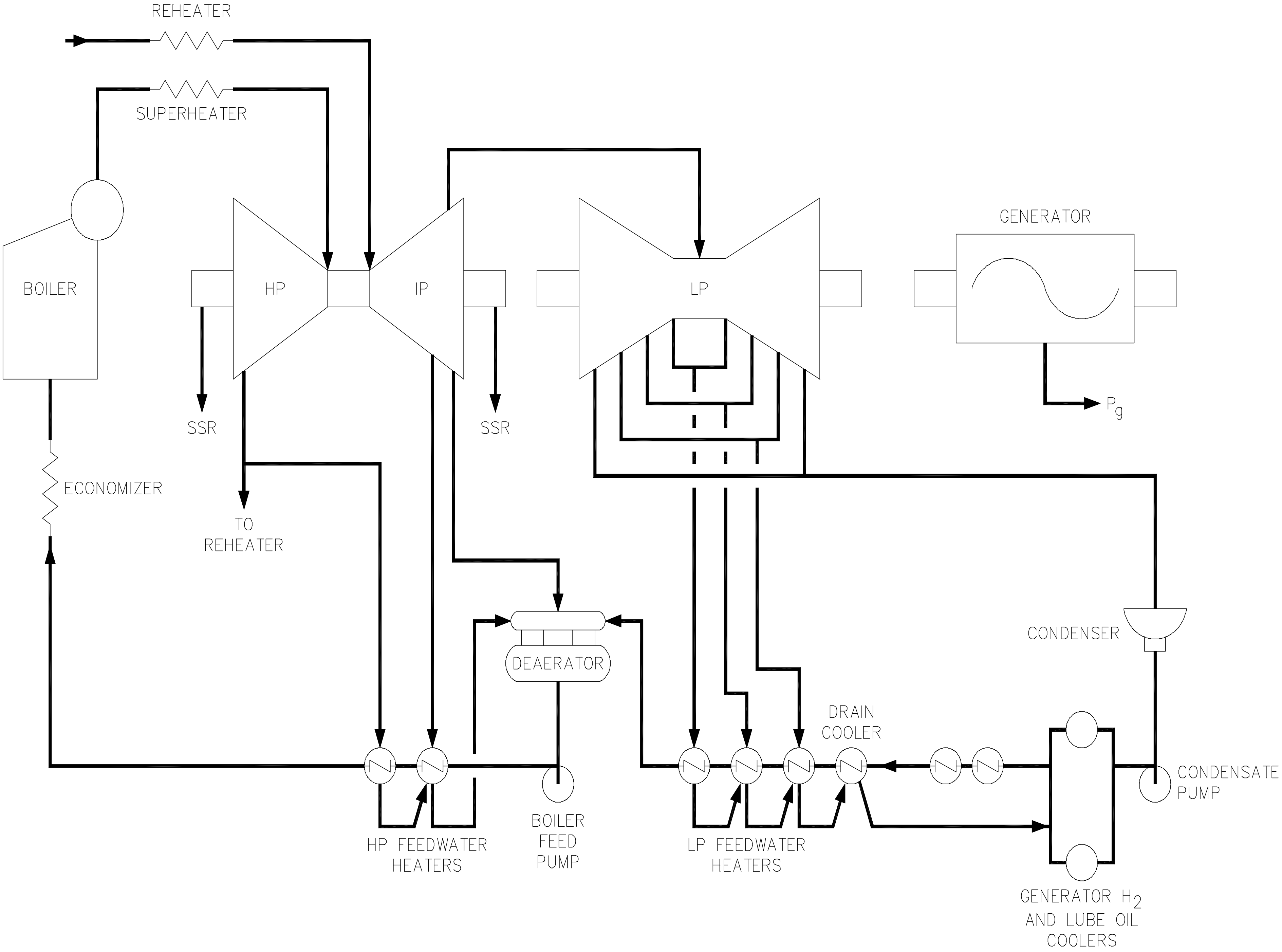
Basic Steam Cycle

Simple Steam Cycle

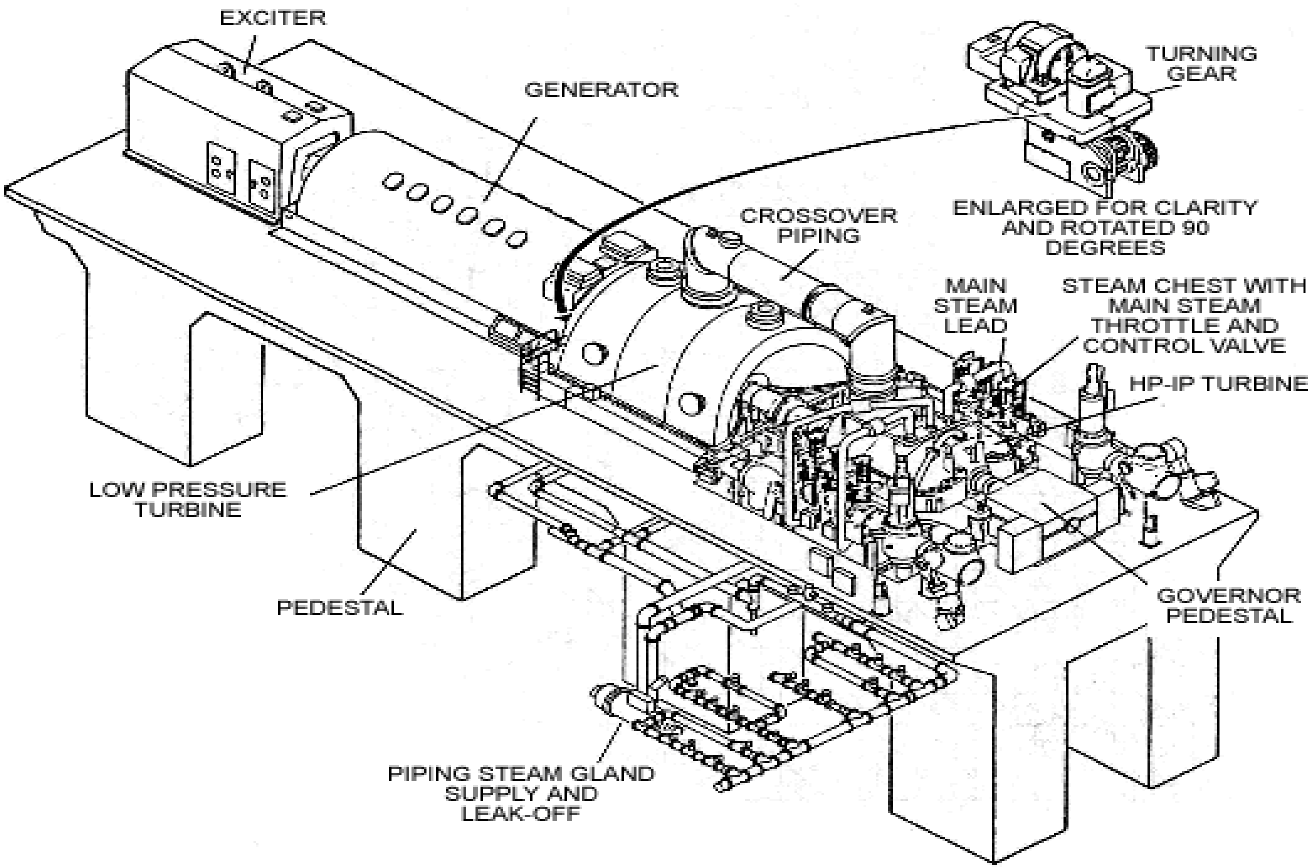
- Four Phases - Steam/Water Cycle
  - **Generation** (Boiler/Reactor/Steam Generator)
    - Heat is produced to change water to steam
    - Changes chemical or Nuclear energy of fuel to thermal energy of steam
  - **Expansion** (Turbine)
    - Nozzles direct steam flow onto blades
    - As the steam expands, the pressure changes cause rotation of the turbine
    - Changes thermal energy to mechanical energy.

Simple Steam Cycle

- Four Phases - Steam/Water Cycle
  - **Condensation** (Condensate System)
    - Remaining low energy steam is cndensed to water removing latent heat
    - Recover and clean up the condensate
    - Largest efficiency loss in the cycle
  - **Feedwater** (Feedwater System)
    - Increases energy, both thermal (temperature) and potential (pressure) of water returning to the system
    - Increases overall plant efficiency


REHEATER
SUPERHEATER
BOILER
HP
IP
LP
GENERATOR
SSR
SSR
P_g
TO REHEATER
ECONOMIZER
DEAERATOR
CONDENSER
DRAIN COOLER
CONDENSATE PUMP
BOILER FEED PUMP
HP FEEDWATER HEATERS
LP FEEDWATER HEATERS
GENERATOR H_2 AND LUBE OIL COOLERS

The Steam Turbine



A TYPICAL POWER STATION STEAM TURBINE AND ITS EXTERNAL EQUIPMENT

2012 Tisina Energy Solutions, LLC

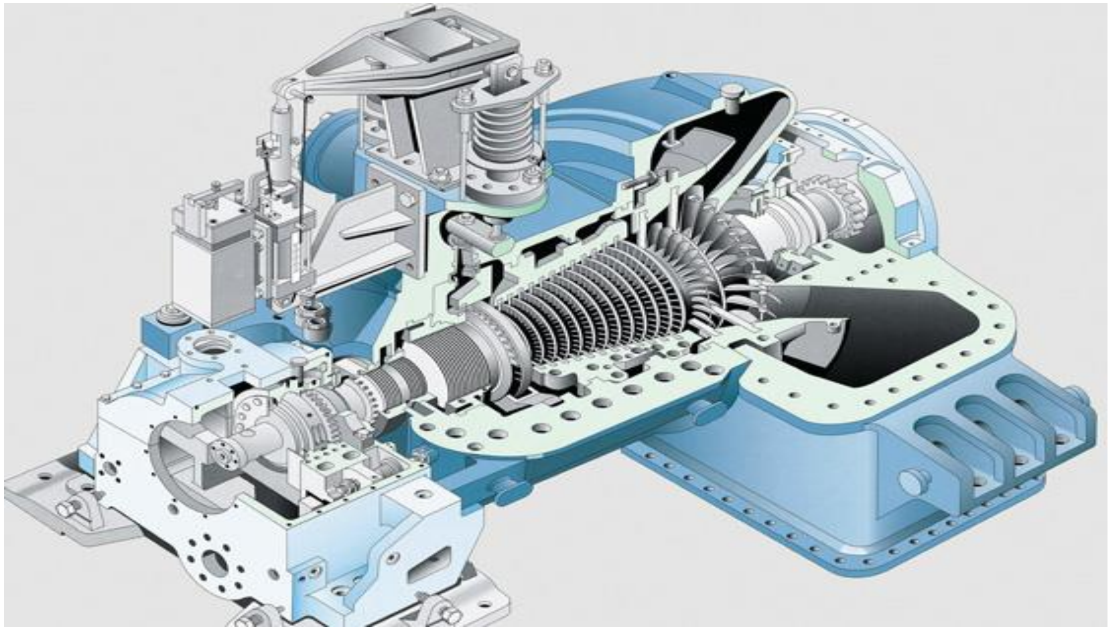
The Steam Turbine

- Steam Turbine: Form of heat engine with the function of converting thermal energy into a rotating mechanical energy
- Two steps are required to convert the thermal energy of the steam into useful work:
    - Thermal energy of the steam is converted into kinetic energy by expanding the steam in stationary nozzles or in moving blades
    - Kinetic energy is converted into work when the steam passes through the moving blades

- http://www.youtube.com/watch?v=qvIi3JDkADI

The Steam Turbine

- Turbine is made up of four fundamental components;
    - Rotor: carries the blades or buckets
    - Nozzles: flow passages for the steam
    - Stationary parts
    - Foundation: support for the rotor & stationary parts



The Steam Turbine

- Turbine Stages
  - High Pressure Turbine (HP)
    - Supplied by Main Steam
    - Exhausts some type of Reheater
  - Intermediate Pressure Turbine (IP)
    - Supplied by Reheated Steam
    - Exhausts to Low Pressure Turbine
  - Low Pressure Turbine (LP)
    - Supplied by IP Turbine exhaust
    - Exhausts to Condenser
- At each stage the steam gives up more energy, and expands, so the turbine stages get progressively larger

The Steam Turbine

- Auxiliary Turbine Equipment
  - **Bearings** - 2 types
    - *Thrust* - axially locate the turbine shaft
    - *Journal* - support the weight of the shaft
  - **Shaft seals** - series of ridges and grooves around the housing to reduce steam leakage
  - **Turning gear -** slowly rotates the turbine, after shutdown to prevent bowing of the shaft and to even out temperature distribution
  - **Vibration Monitors** - measure the movement of the shafts in their bearings to prevent wear or unbalaced conditions before damage can occur

The Steam Turbine

- Turbine Operating Limitations:
  - The Turbine Shaft
    - Eccentricity: shaft out of concentric round
    - Differential expansion: rotor and turbine casing heat up and expand at different rates
    - Bearing vibration limits
    - Critical speed: harmonics due to natural resonance
  - The Turbine Blades
    - Back pressure limitation: fatigue cracks and harmonics on low pressure blades
    - Erosion due to moisture (high moisture content in the steam)
    - Solid particle erosion (carryover from the boiler/SG)
    - Silica plating (can unbalance the blades)

The Condensate System

- Major Components
    - **Condenser**: converts the exhaust steam into water after it leaves the last stage of the turbine
    - **Hotwell**: receptacle where water is collected from the condenser
    - **Hotwell Make-up / Draw-off valves**: compensate for losses or excesses to or from the condensate storage tank
    - **Demineralizers**: Clean up the condensate
    - **Condensate Pumps:** Move condensate up to the feedwater system

The Condensate System

- **Deareator**: removes non-condensible gases (mainly oxygen) from the condensate
- **Boiler Feed Pump**: supplies water to the boiler/SG and has to overcome boiler pressure, friction in the heaters, piping, and economizer
- **Feedwater Heaters:** preheats the feedwater before entering the boiler/ SG
    - The plant may have multiple “strings” or series of Feedwater heaters

Start-Up Systems

- In order to prevent thermal stress damage, the turbine blades, housing, and other components must be slowly warmed up to normal operational temperatures before the plant can begin producing power
- Plant start-up systems provide a minimum flow path using main steam as the plant begins it’s start-up process
- This allows a slower, controlled warming process that is less likely to cause damage
- It also provides a steam source for de-aeration of feedwater and a means of heat recovery during plant start-up, which also increases overall efficiency

Other Common Plant Systems

- **Gland sealing**: enable the turbine to be sealed where the shaft exits the casing (keep air out, steam in)
- **Hydrogen Cooling System**: cooling water coils in the generator to cool the hydrogen gas
- **Hydrogen Seal Oil System**: seals the generator where the shaft exits the casing keeping the hydrogen in
- **Cooling Water:** Cools the various component systems
- **Circulating Water:** primarily provides the cooling water for the condenser
- **Turbine Lube Oil:** supply clean, pressurized oil at proper temperature
- **Fire Protection:**

Other Common Plant Systems

- **Service Air:** Various pressurized air needs within the plant
- **Control Air:** used on pneumatic or instrumentation applications where moisture cannot be tolerated
- **Waste Water Treatment:**
- **Station Batteries:** Supply critical plant loads (turning gear)

Possible Environmental Limitations on Plant Power Output

- Maximum allowable water temperature of cooling water return to river or lake
- Maximum allowable values of substance discharged to the atmosphere
  - Nitric Oxide - NOX
  - Sulfur Dioxide - SO_2
  - Carbon Monoxide – CO
  - Carbon Dioxide – CO_2
  - Particulates – Opacity
- pH (solubility) of discharged cooling water
- Turbidity of discharged cooling water -suspended solids such as sediment, mud, and dirt that are in the water

Possible Operational Limitations on Plant Power Output

- Dissolved solids: minerals picked up by the water that will form hard adherent deposits on the internal surfaces of the boiler or heat exchangers
- Dissolved Oxygen: entrapped in water, could attack metal parts including feedwater, condensate, and boiler tubes
- Iron: concentration must be at a certain level in order to raise temperatures in a supercritical unit, but excess iron deposits can limit the heat transfer rates in boilers, or cause “hot spots”, increasing corrosion
- Silica: found in water as a dissolved solid. Can solidify on components and create scale or reduce heat transfer

Possible Operational Limitations on Plant Power Output

- **High condenser backpressure** is another factor that may limit power output
    - High cooling water temperatures may not condense the steam as efficiently
    - Condenser tubes may spring leaks and allow air to enter the condenser, compromising the vacuum
    - The condenser tubes may become dirty, preventing adequate cooling of the steam
    - A reduced condenser vacuum limit the amount of steam that can be pushed through the turbine, forcing a reduction in plant power output

Agenda

- Elements of the Energy Conversion Process
- Provide an overview of:
  - Steam/Condensate/Feedwater and other Common Systems
- Describe the various types of units:
  - Fossil generating units
  - Nuclear generating units
  - Hydroelectric generating units
  - Combustion turbines
  - Combined Cycle Power Plants (CCPP)
  - Wind Units
  - Solar Units

Fossil Generation

Fossil Generation - Types

- Fossil Plants include those powered primarily by Coal, Oil, Natural Gas, or a combination of these fuels
  - Combined, these fuel sources currently provide about 70% of the PJM area generation
  - Total power output can be as low as 15-20 MW or as high as 1,450 MW
  - **Ramp Rate**, or the rate of change of power output, ranges from a few MW/min. on older units to 10-20 MW/min. for newer units
  - Each fuel type requires a unique set of components to control the ignition and combustion of the fuel, and handle the by-products of that combustion process

Fossil Generation - Components

- In a fossil plant, the combustion of the fuel takes place within the **Boiler**
  - A Boiler is some type of closed vessel in which water is heated, steam generated, and superheated under pressure by the application of additional heat
  - Basic functions of a boiler:
    - Pressure containment
    - Heat transfer
    - Steam separation
  - Two types of boilers:
    - Subcritical (drum type)
    - Supercritical

Fossil Generation - Components

- Drum Type Boilers:
  - Drum Type Boiler Components
    - **Economizer** - Improves boiler efficiency by extracting heat from the flue gases and transferring it to the feedwater
    - **Steam Drum** - Separates the water from the steam generated in the furnace walls
    - **Downcomers** – Act as a return path for the feedwater back to the boiler; located away from main heat source
    - **Mud Drum** - Fed from downcomers; collection point for sentiment and impurities

Fossil Generation - Components

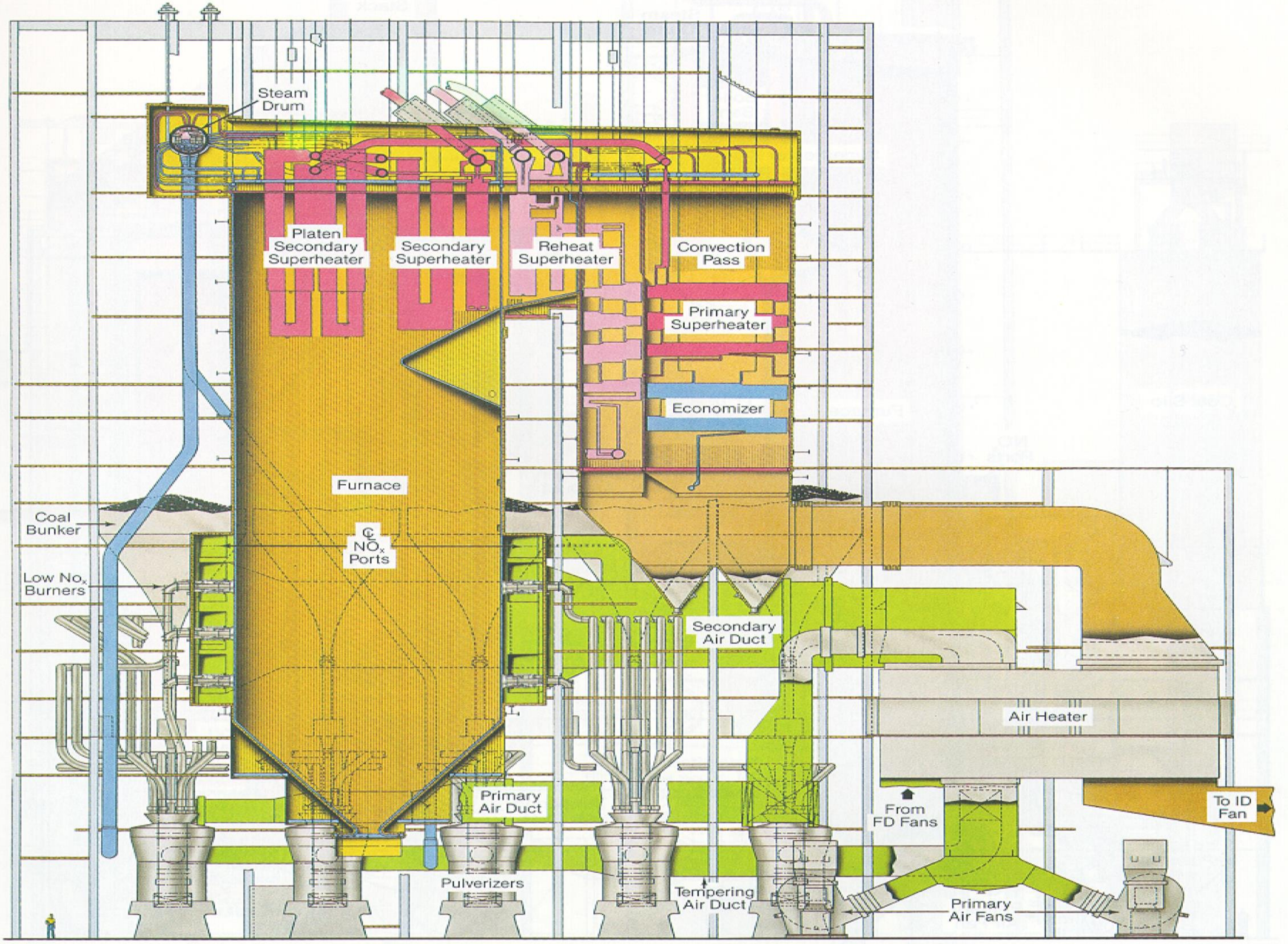
- **Superheater** - Increases cycle efficiency by adding heat to raise the steam temperature above its saturation point; located in the flue gas path
  - Adds ~ 3% efficiency per 100°F
  - There are 2 types of Superheaters;
    - Radiant: Direct radiation from the furnace
    - Convection: Absorb heat from hot gases
- **Reheater** - Adds energy back to the steam that has been passed through the HP turbine
  - Adds 4-5 % efficiency per 100°F

Fossil Generation - Components

- Super Critical Boilers :
  - Operate at significantly higher temperatures and pressures (>3200 psi and over 700 °F)
  - Water is directly converted to steam within the water wall tubes, without going through a boiling process
    - Do not have a boiler drum
  - “Once-thru” design – no recirculation process
  - Many circuits of superheaters
  - More efficient in certain MW ranges

Fossil Generation - Components

- Modifications are needed for the turbines used in supercritical units, due to the higher temperatures and pressures
  - Stronger materials for rotor forgings, casings, steam lines and valves
    - Iron based materials replaced by nickel based superalloys
    - Last stages of turbine blades also use special alloys


Steam Drum
Platen Secondary Superheater
Secondary Superheater
Reheat Superheater
Convection Pass
Primary Superheater
Economizer
Furnace
Coal Bunker
℄ NO$_x$ Ports
Low No$_x$ Burners
Secondary Air Duct
Air Heater
Primary Air Duct
From FD Fans
To ID Fan
Pulverizers
Tempering Air Duct
Primary Air Fans

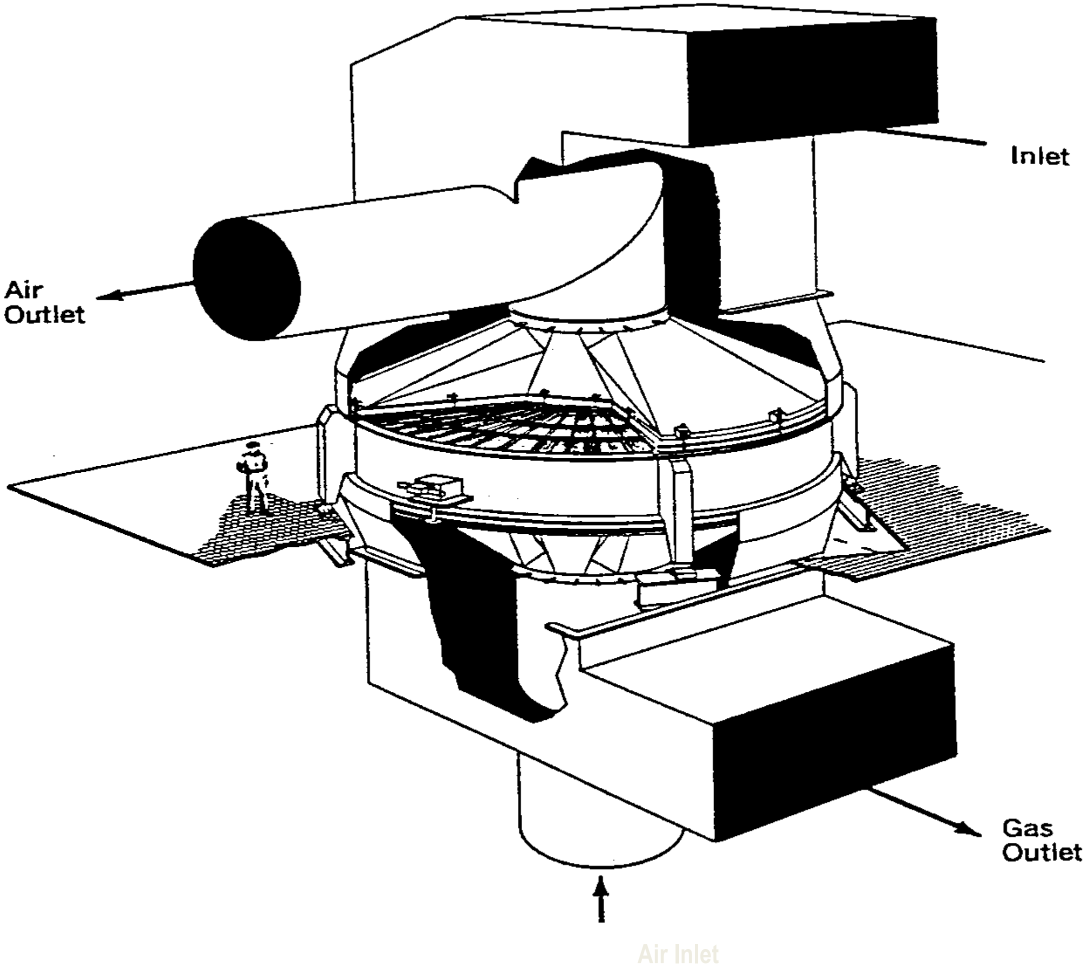
Fossil Generation - Components

- Super Critical Boilers
  - Advantages
    - Greater efficiency (45%)
    - Faster response to changing load
    - Reduced fuel costs due to thermal efficiency
    - Lower emissions (CO_2, NO_x, SO_x)
  - Disadvantages
    - Long start-up time
    - Expensive to build (greater press. / temp.)
    - Loss of circulation causes serious boiler damage

Fossil Generation - Components

- Furnace Air Systems
  - **Air Heaters** - Used to transfer heat from stack flue gases to pre-heat the combustion and primary air
  - **Forced Draft Fans -** Used to maintain windbox and secondary air pressure to accelerate combustion
  - **Induced Draft Fans -** Used to maintain a negative furnace pressure
    - Always larger than FD due to combustion gas expansion

Air Heater



Miscellaneous Fossil Plant Systems

- Bottom Ash (slag) Handling System: remove the course, granular, incombustible by-products from the bottom of the boiler
- Fly ash handling system: remove the fine-grained, powdery particulate that is found in flue gas
- Scrubber Facilities: trap pollutants and sulfur that is produced from burning coal and natural gas from escaping into the air

Fossil Unit Limitations that may affect Power Output

Temperature limits:

- Temperature limit on the furnace water wall caused by increases in pressure and final steam temperatures to prevent damage to the tubes
- Corrosion of superheater and reheater tubes caused by the increase in steam temperatures
- Loss of Air heater thermal efficiency
  - Increasing feedwater temperature to the boiler leads to a rise in air heater gas inlet temperature, and loss of overall efficiency

Fossil Unit Limitations that may affect Power Output

- Auxiliary equipment outages (scheduled or unscheduled)
  - Heaters, condensate or boiler feed pumps
  - Pulverizers (Mills) or oil pumps, gas
  - Fans: ID, FD, or primary air
  - Pumps: circulating water
  - Fuel
  - Ash handling

Fossil Unit Limitations that may affect Power Output

- Fuel Limitations
  - Coal Issues;
    - Excessive moisture or bad weather can lead to;
      - Difficulty unloading
      - Sliding on conveyor belts
      - Build-up in chutes
      - Frozen coal
    - Poor quality coal can lead to increases in slagging and high ash resistivity
    - Coal must be crushed or pulverized to burn efficiently
      - Degree of crushing depends on burner type
        - Pulverized
        - Stoker
        - Cyclone

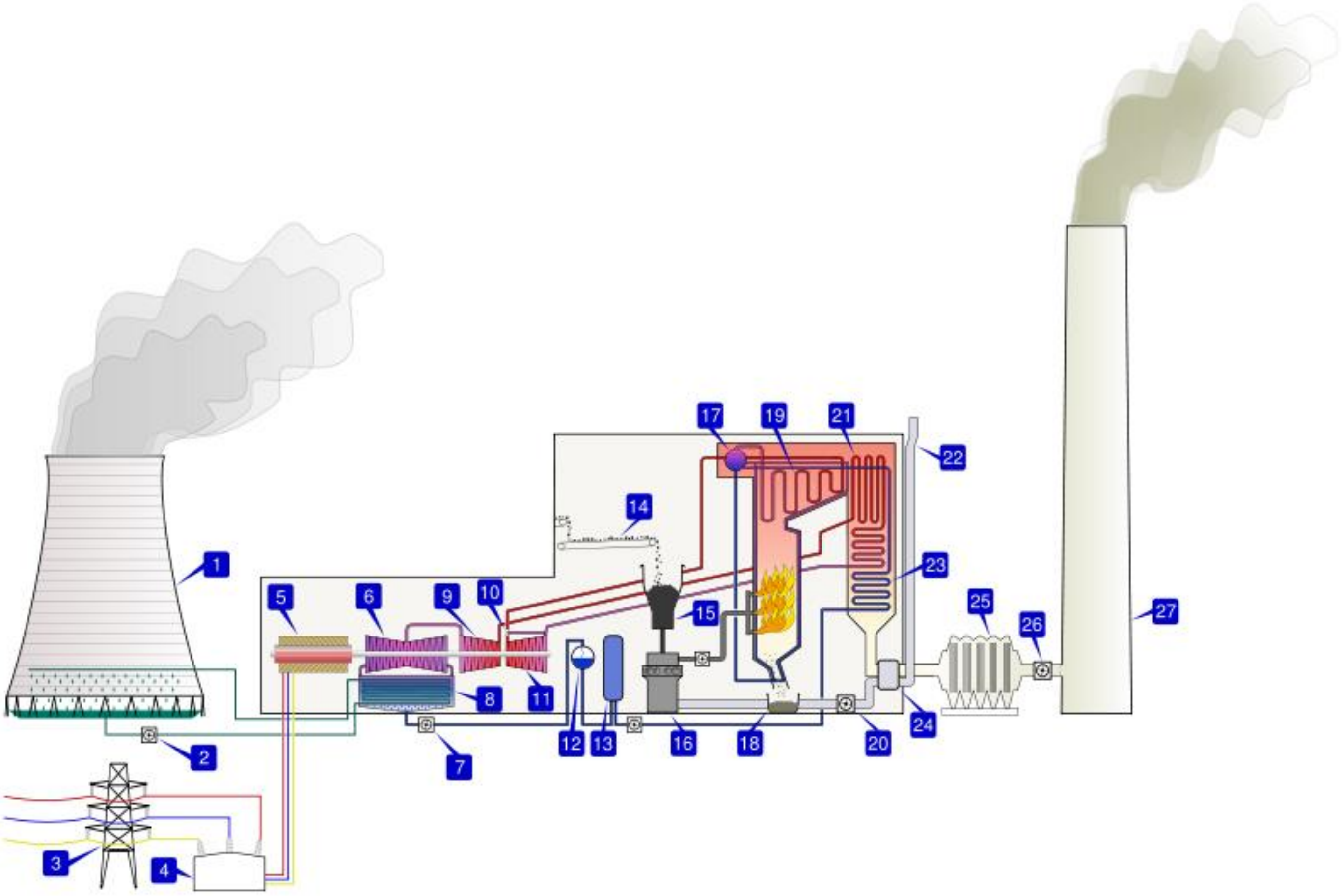
Fossil Unit Limitations that may affect Power Output

- Oil Issues;
  - Moisture deteriorates the performance of oil and increases the probability of corroding components
    - Increased coking
    - More particulates and impurities
  - Fuel oil needs to be pre-warmed to pump properly (150-180 °F) and warmed further to burn efficiently (250-330°F)
  - Oil injectors need to be cleaned and maintained regularly

Fossil Unit Limitations that may affect Power Output

  - Gas Issues;
    - When moisture is present, it interacts with impurities in the gas lines to form a corrosive mixture
  - In all fossil units a major concern is flame detection in the boiler.
- Boiler Water Chemistry - Must be maintained within certain levels to ensure the water wall tubes are not damaged
  - Condenser leaks are the major source of impurities

General Coal Plant Schematic



Key

1. Cooling tower
2. Cooling water pump
3. Three-phase transmission line
4. Step-up transformer
5. Electrical generator
6. Low pressure steam turbine
7. Boiler feedwater pump
8. Surface condenser
9. Intermediate pressure stage
10. Steam control valve
11. High pressure stage
12. Deaerator
13. Feedwater heater
14. Coal conveyor
15. Coal hopper
16. Coal pulverizer
17. Boiler steam drum
18. Bottom ash hopper
19. Superheater
20. Forced draft fan
21. Reheater
22. Combustion air intake
23. Economizer
24. Air preheater
25. Precipitator
26. Induced draft fan
27. Flue gas stack

Nuclear Generation

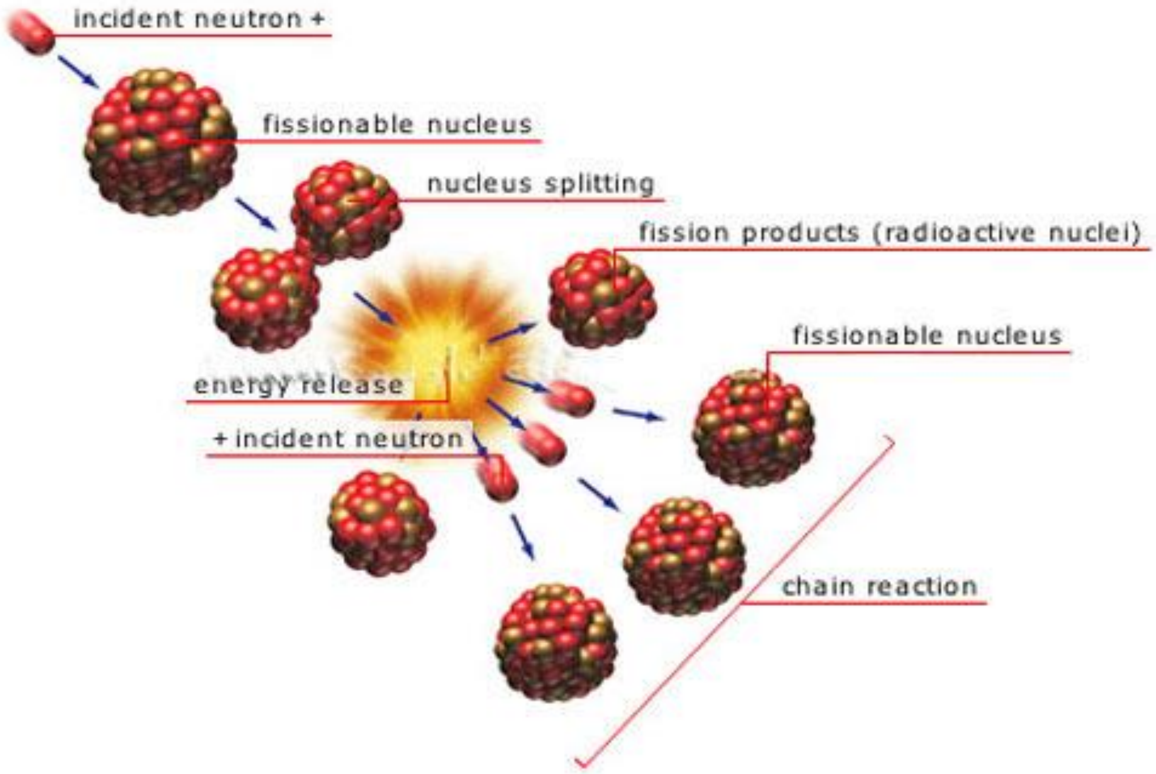
Nuclear Generation

- Nuclear Fission yields the highest amount of energy produced per mass of fuel “consumed” for any existing fuel type

- Nuclear Generation currently supplies about 17% of the PJM area generation
  - Two types of light-water reactors:
    - Pressurized Water Reactor (PWR)
    - Boiling Water Reactor (BWR)
    - In the US, PWR’s outnumber BWR’s by about 2 to 1
  - Light-water reactors use ordinary water to slow down the thermal neutrons produced in the reaction
  - Light-water reactors use enriched uranium, U^{235}

Nuclear Generation

- The fission process or the “splitting apart” of an atom is what produces heat in a nuclear reactor



Nuclear Generation

- Conventional light water reactors utilize fuel with an initial 235U concentration enriched to at least 3.5%
- Fuel is loaded at 3.5% 235U and replaced once the concentration has fallen to 1.2%
- A 1000 MW plant would consume ~30 tons of fuel per year in comparison to 9,000 tons of coal per day for a fossil plant of the same magnitude
- Nuclear Units require a **Coolant**, to remove the heat from the fission process (and produce the steam for the turbines) and a **Moderator.** The Moderator slows down the neutrons to allow the fission process to occur
  - In a light water reactor, water is used as both the Moderator and the coolant

Nuclear Generation

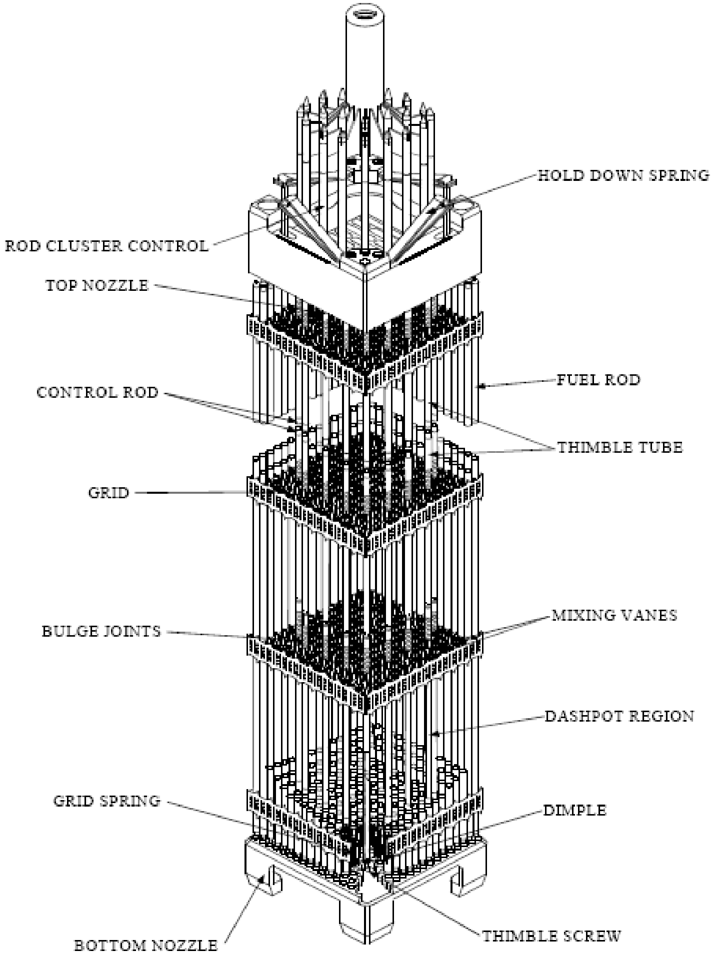
- Once the steam is generated in a Nuclear Unit, it follows the same Cycle as that used in Fossil Units
  - The Steam is directed to Turbine/Generator assembly to produce Power
  - The Used Steam is sent to a condenser to be turned back into condensate, and non-condensible gasses are removed*
  - The condensate is cleaned up, reheated through feedwater heaters, and sent back into the steam cycle*

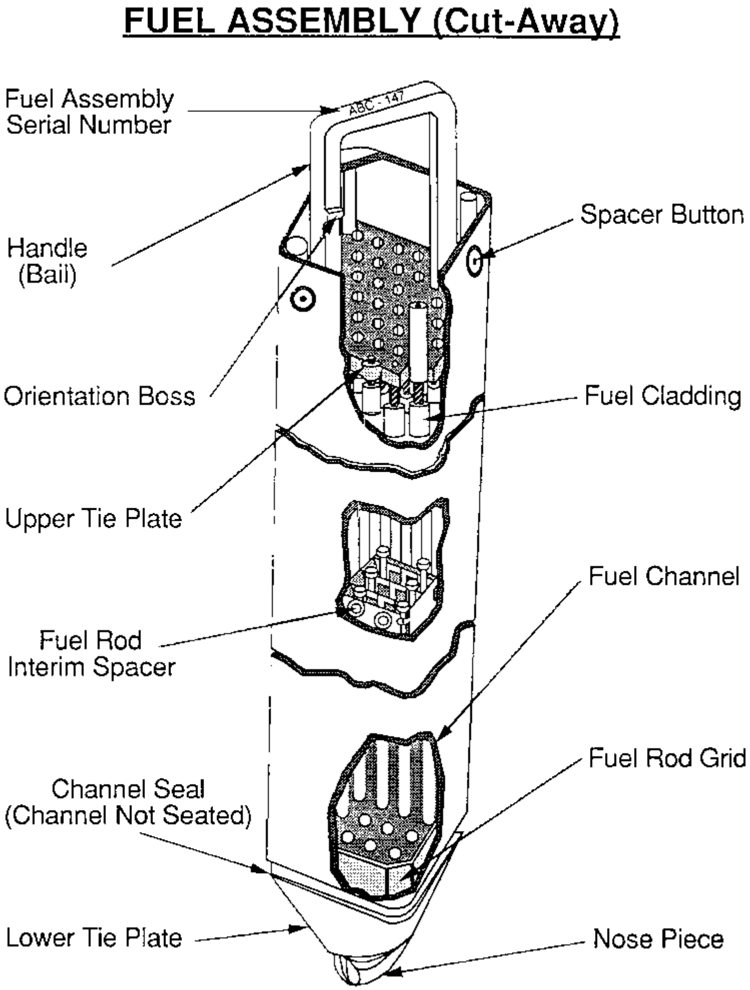
* BWR Units modify this component slightly

Fuel Assembly

- Both PWR and BWR fuel assemblies consist of the same major components:
  - Fuel Rods - ~ 12 feet long, made up of stacks of ceramic fuel pellets arranged in a square matrix
    - 17 X 17 for PWRs 8 X 8 for BWRs
  - Spacer Grids – provide rigidity for the assembly and allow coolant to flow up around the fuel rods
  - End fittings – the top and bottom structural portions. Also helps direct coolant through the assemblies
  - BWR Fuel Assemblies are also surrounded by a Fuel Channel, to provide more surface areas for steam bubble formation

Fuel Assembly



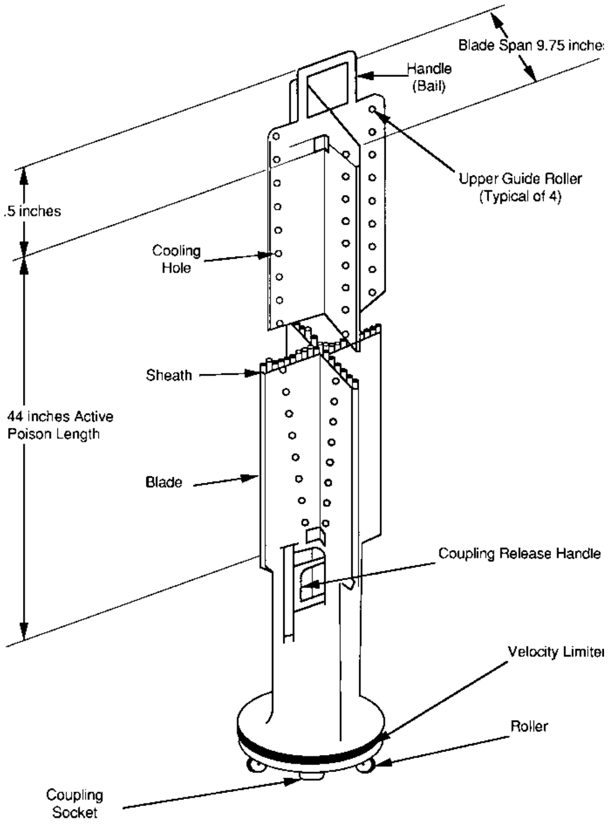


Nuclear Generation

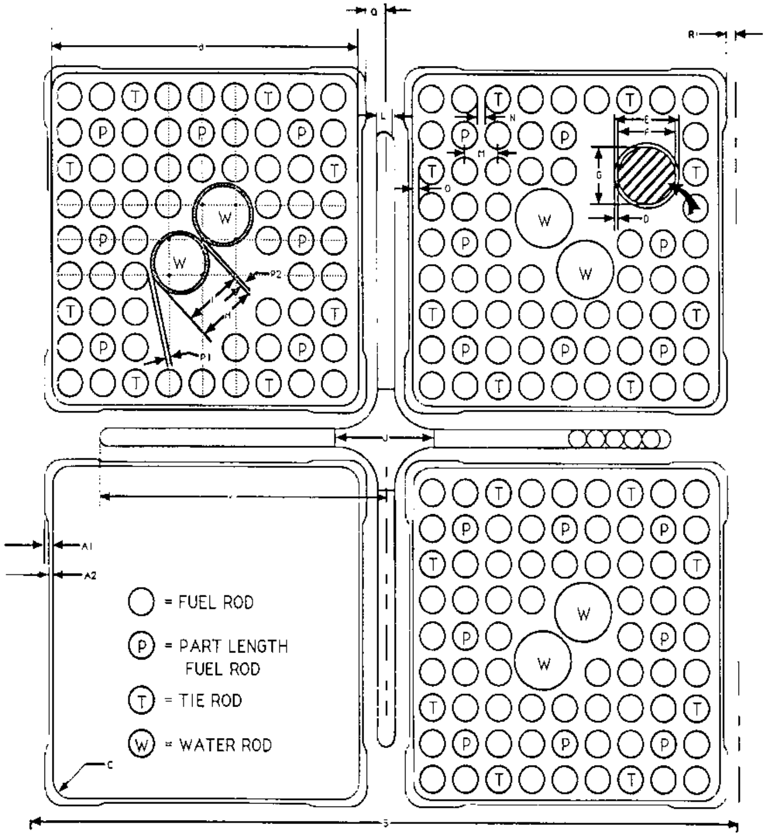
- Nuclear Units also use Control Rods to help moderate (BWRs) or Shut down (both types) the fission reaction
- A Control Rod is a cross-shaped blade made of stainless steel containing Boron or other neutron-absorbing materials.
- The Boron will “absorb” the thermal neutrons and slow or stop the Nuclear fission process
- A SCRAM is an automatic process that simultaneously inserts all control rods into the core, to quickly stop the fission process and stop the reaction
    - SCRAMs can also be manually initiated from the control room or other remote locations

Control Rod

CONTROL ROD ASSEMBLY



FUEL ROD ARRANGEMENT
GE 11 DESIGN

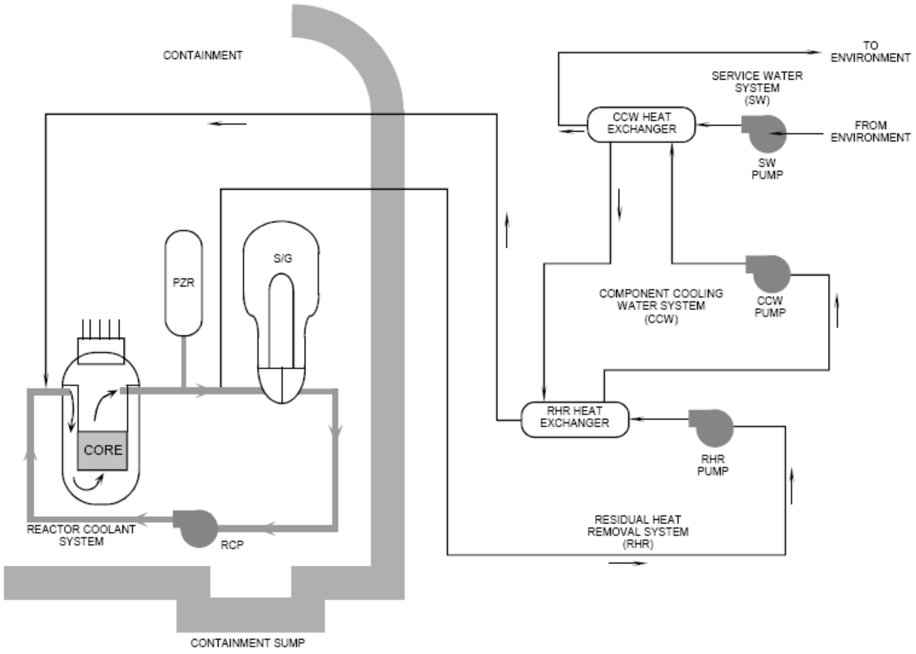


Systems common to both designs

- PWRs and BWRs differ in some critical design elements, but both share some overall design components
- Even if the Nuclear Reaction in the core is shut down, the vibration of the fission products is sufficient to ensure that the core will produce a substantial amount of heat for some time after plant shut down (**Decay Heat**)
- The plants must have some mechanism to remove this heat to prevent damage to the core components at times when the main steam cycle is not available to remove the heat
- **Residual Heat Removal** Systems are used as a secondary means of removing heat from the core and transferring it to the environment

Systems common to both designs

- **Residual Heat Removal** Systems use a series of heat exchangers to bypass the steam generator / condenser and transfer the decay heat to the ultimate cooling source

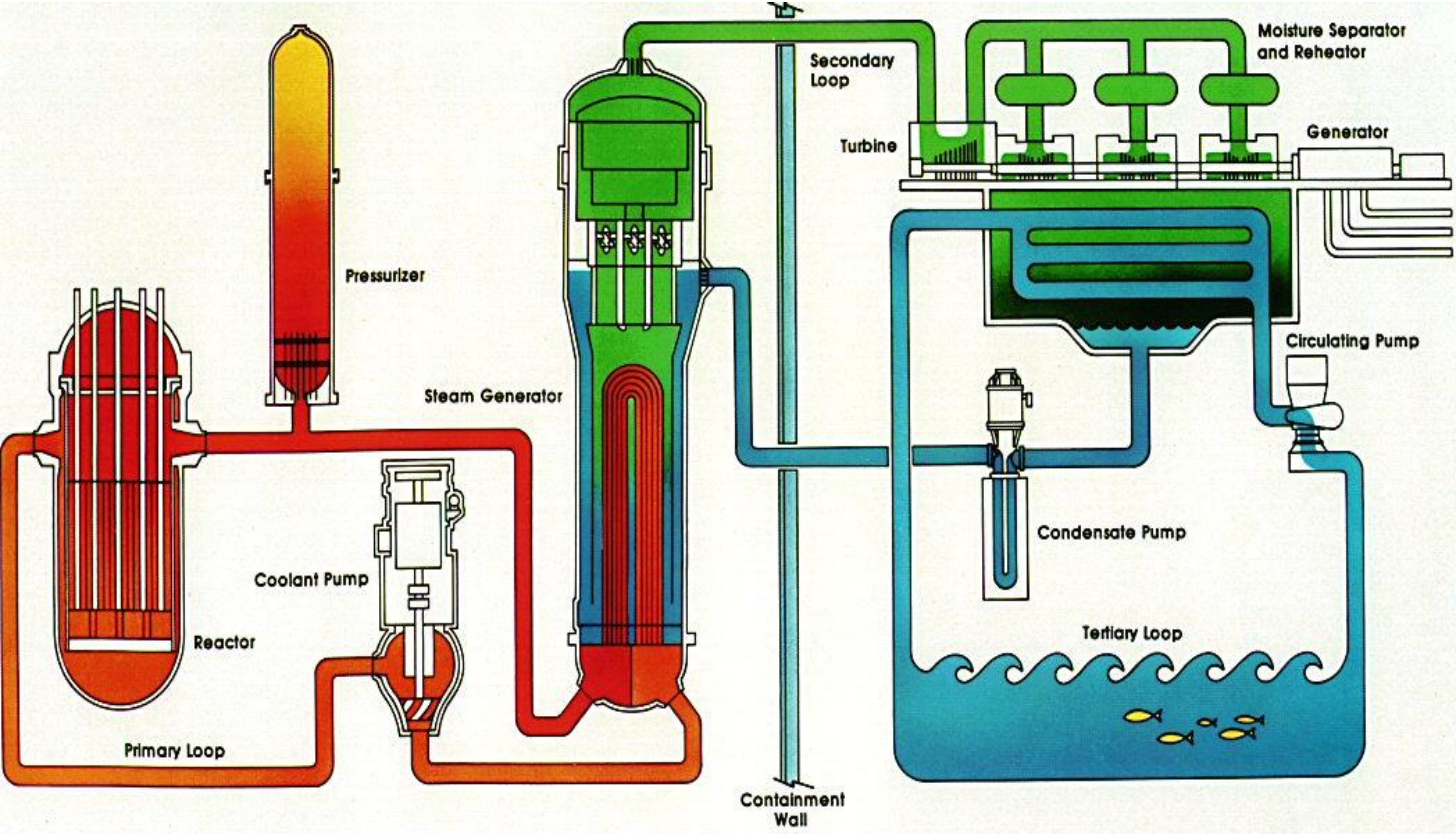


Systems common to both designs

- **Emergency Core Cooling Systems**
  - Nuclear plants are designed to cope with a leak in their primary reactor vessel, or the associated piping without releasing radioactive materials to the environment
  - Both types of plants maintain 4 redundant systems to provide more water than normally required to the core to make up for losses due to the leakage
    - 2 systems are high pressure / low volume systems. These are used when the leak is not sufficiently large to cause the reactor vessel to depressurize, and a high pressure head must be pumped against
    - The other 2 systems are designed for low pressure / high volume situations where a catastrophic failure has allowed the vessel to depressurize and large volumes of water are being lost
  - Both types of plants are designed to contain the water within the Primary containment buildings until the situation is under control

Pressurized Water Reactor

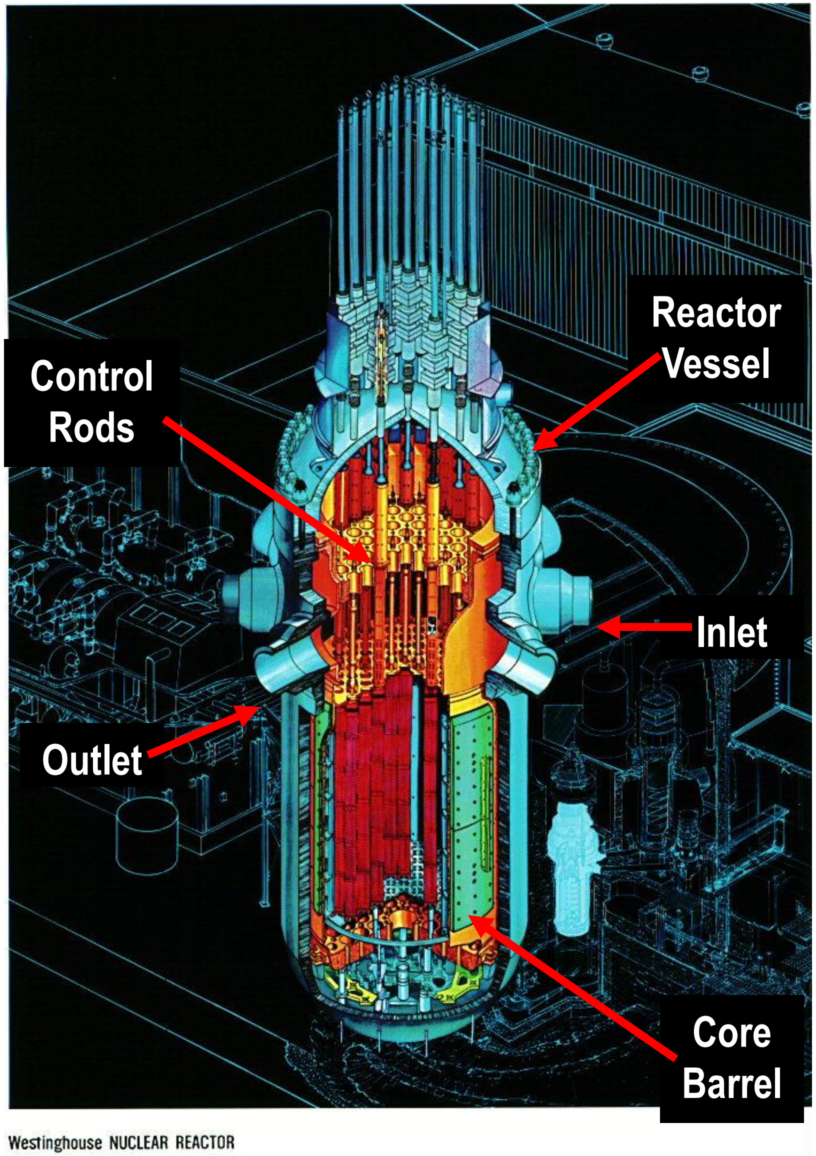
- Major Design Factors for a PWR:
  - The water in the Reactor is not designed to boil. It is maintained under higher temperatures and pressures by the **pressurizer**
    - ~600 °F at 2250 psi
  - The Primary Coolant is sent to a **Steam Generator** where clean (non-contaminated) water is boiled to make steam
    - This means the Generator and Condenser components never come into direct contact with Nuclear materials
  - Power Levels are controlled by adding or removing Boron (in the form of Boric Acid) to the primary coolant.
    - This is accomplished by the **Chemical Volume & Control System**
  - Control Rods drop into the core from the top of the Reactor Vessel



Nuclear Steam Supply System

MB 3618A

Pressurized Water Reactor



Westinghouse NUCLEAR REACTOR

Water flows downward on the outside of the core barrel to the bottom of the reactor. The flow then turns upward in between the fuel rods from the bottom to the top of the reactor.

The water leaves the reactor on it way to the steam generator

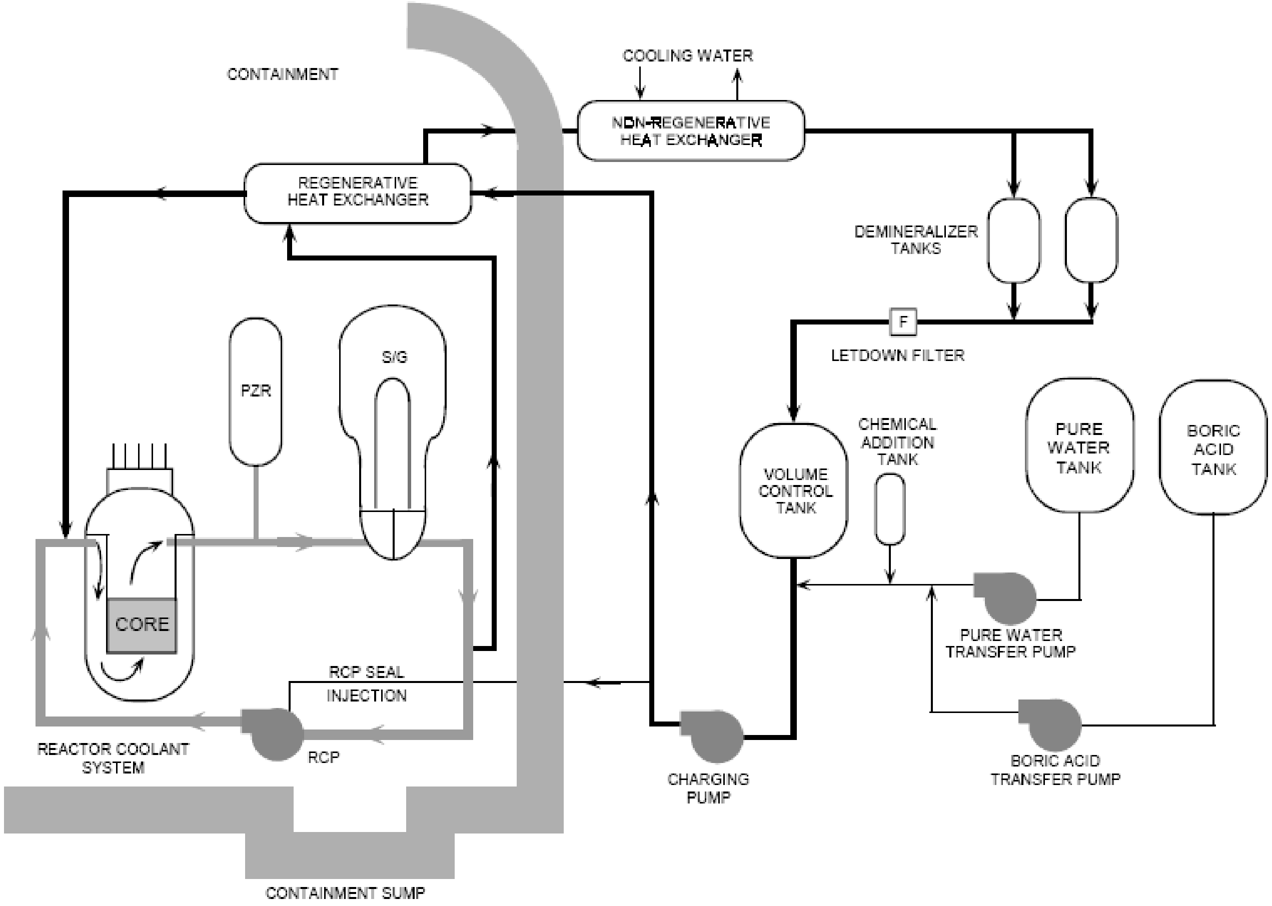
PWR Components

- The **Reactor Coolant Pumps** provide the motive force to pump water through the Reactor vessel, to the Steam generators to remove the heat from the Fission process, and back into the Reactor Vessel
- Reactor Coolant Pumps are rated for 6,000 to 10,000 HP each – delivering approximately 100,000 gallons of coolant per minute per pump
- Generally, PWR’s have 2 to 4 coolant pumps per Vessel, each feeding a separate Steam Generator

PWR Components

- The **Pressurizer** is the component in the reactor coolant system which provides a means of controlling the system pressure due to changes in coolant temperature
  - The Pressurizer operates with a mixture of steam and water in equilibrium
- The **Chemical and Volume Control System** is a major support system for the reactor coolant system
  - Purifies reactor coolant using filters and demineralizers
  - Adds and removes boron to control Reactor power Levels
  - Maintains the pressurizer level at the required set point

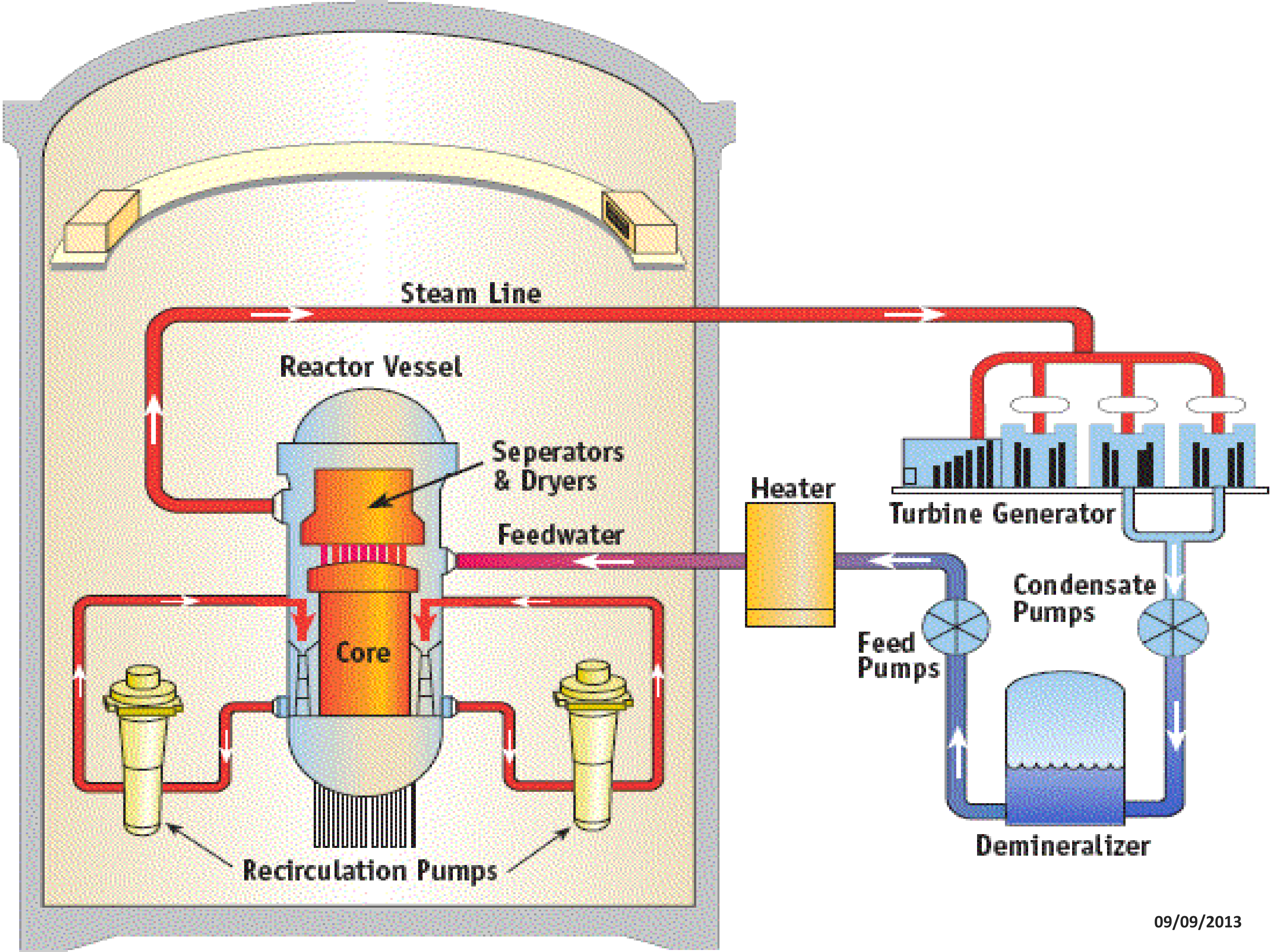
PWR Components



Chemical and Volume Control System

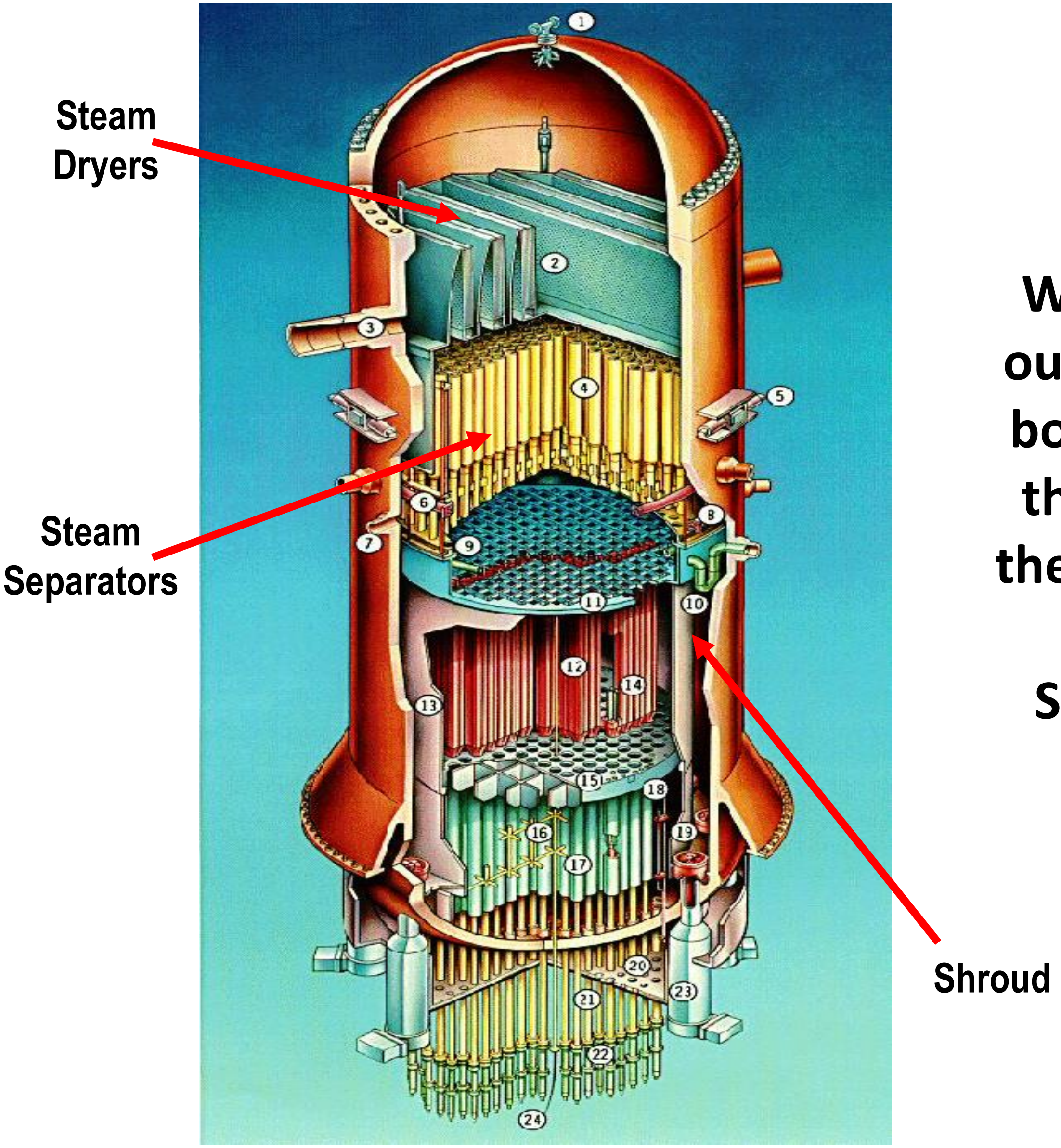
Boiling Water Reactor

- Major Design Factors for a BWR:
  - The water in the Reactor does boil. Lower temperatures are pressures are requires
    - ~550 °F at 1000 psi
  - A Steam Separator and Steam Dryer are installed above the reactor core to dry the steam prior to sending it to the main Turbine
    - This means the Generator and Condenser components do come into direct contact with Nuclear materials
  - Power Levels are controlled by adjusting the position of the control rods in the core and by adjusting the rate of coolant flow through the core
  - Control Rods are inserted into the core from the bottom of the Reactor Vessel


Steam Line
Reactor Vessel
Seperators
& Dryers
Feedwater
Heater
Turbine Generator
Core
Condensate
Pumps
Feed
Pumps
Demineralizer
Recirculation Pumps

09/09/2013

Boiling Water Reactor

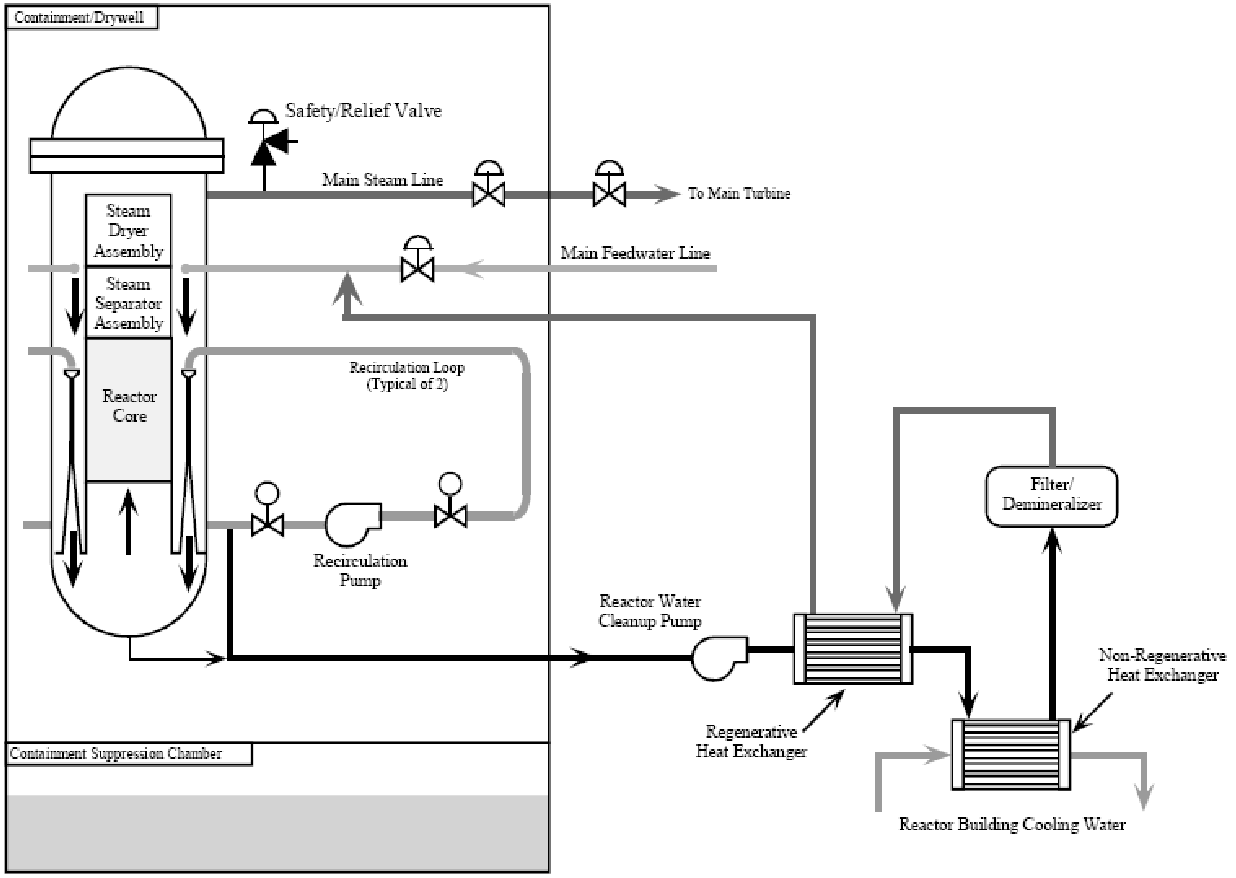


Water flows downward on the outside of the core barrel to the bottom of the reactor. The flow then turns upward in between the fuel rods from the bottom to the top of the reactor.
Steam is separated at the top from the water.

BWR Components

- Like any vessel that you boil water in, the Reactor Vessel of a BWR tends to concentrate the impurities in the water, and that could damage the components
- The **Reactor Water Clean-up System** takes a suction off each jet pump and off the bottom of the vessel and runs a portion of the water through a set of demineralizers to attempt to remove these impurities
- The RWCU water is passed through 2 sets of heat exchangers to cool it from vessel conditions to near ambient, to avoid damage to the demineralizer resins

BWR Components

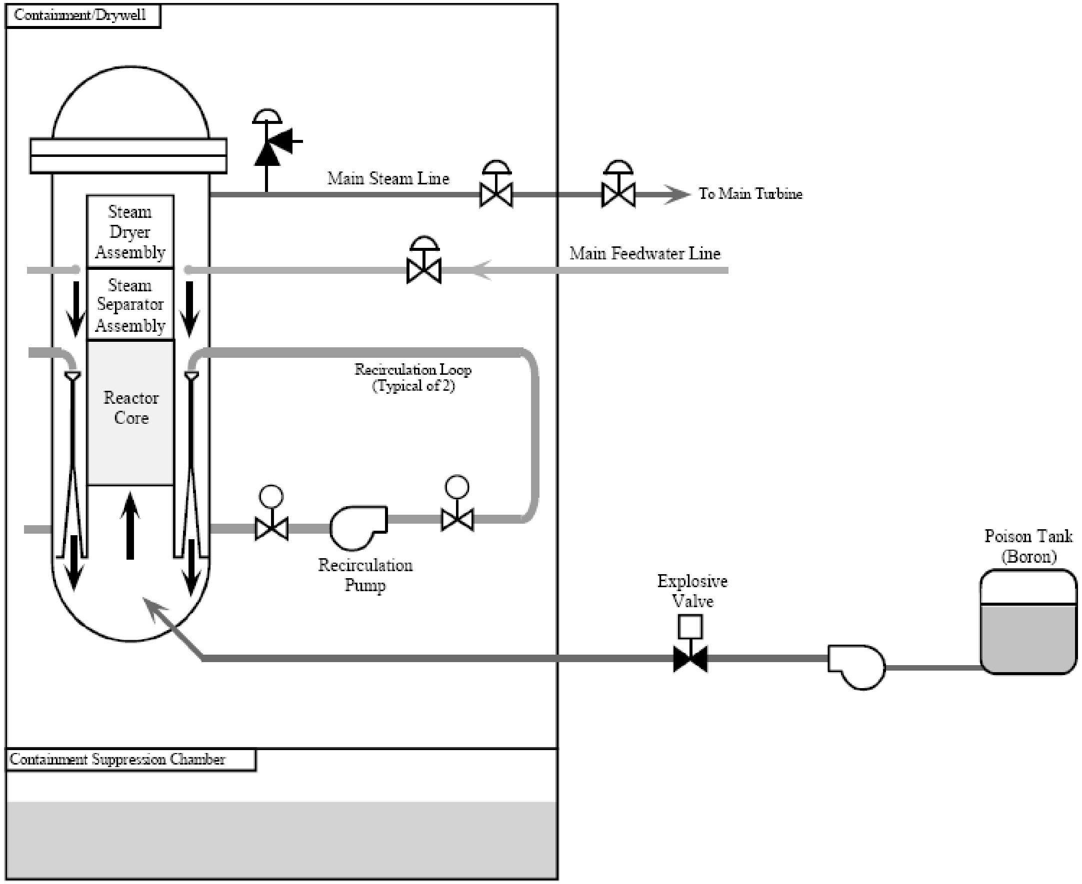


Reactor Water Cleanup System

BWR Components

- Because the Control Rods on a BWR are inserted from the bottom of the vessel, a failure of the Control Rods to insert would not be helped by gravity alone
- A redundant system called **Standby Liquid Control** provides a tank of highly concentrated boron solution adjacent to the reactor. If the Control Rods fail to shut down the fission reaction when required, an explosive valve if fired, dumping the tank contents into the reactor vessel and shutting down the chain reaction
- Since BWRs do not have the Chemical and Volume control systems of PWRs, this is likely a one-time event for a BWR – it could never be restarted

BWR Components



Standby Liquid Control System

BWR Components

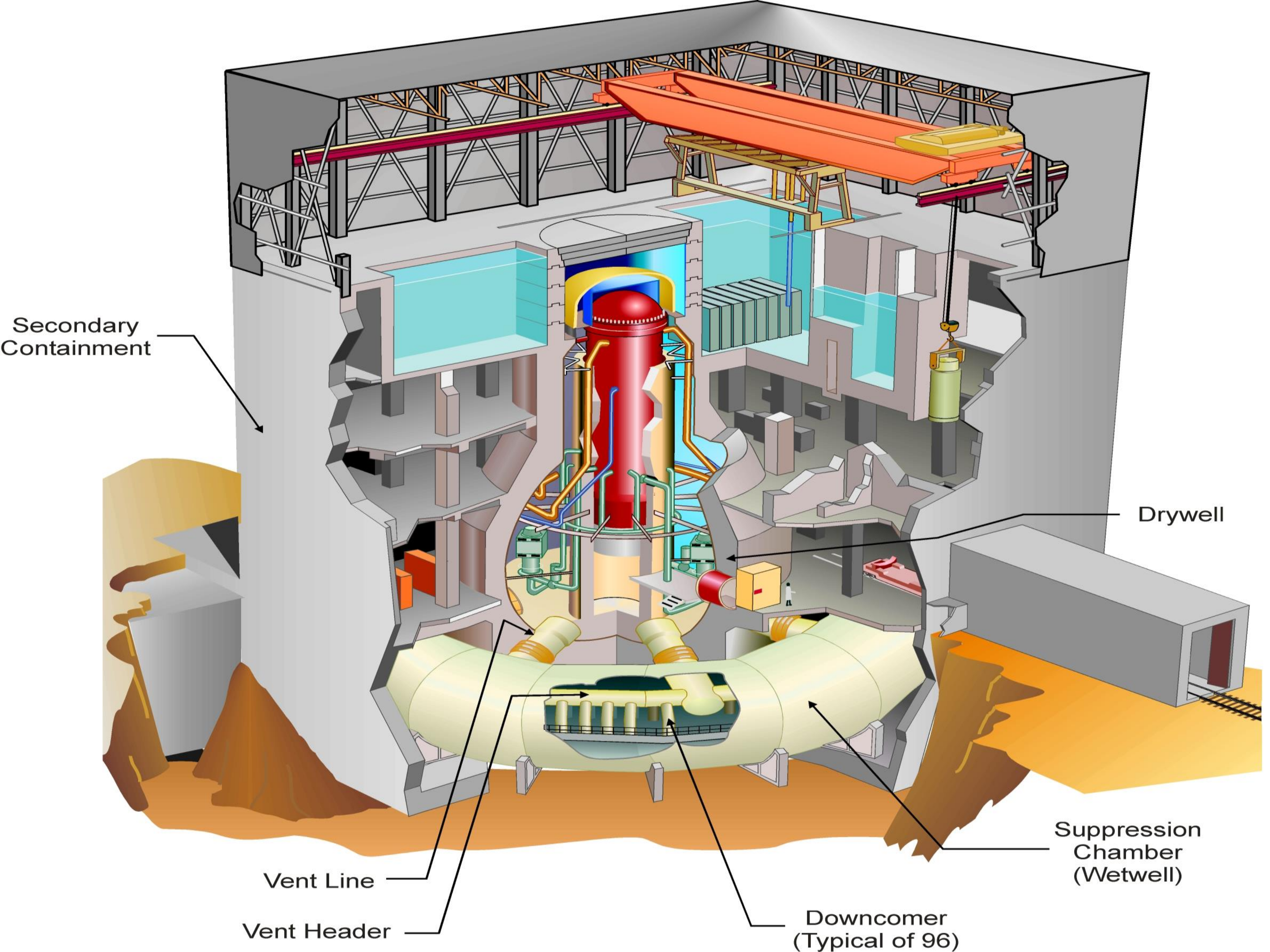
- In a BWR, the steam coming off the reactor contains other gasses as well;
  - Fission Gas by-products from the core that are carried over
    - Xenon, Iodine isotopes
  - Normal gasses present in the atmopshere that have been “activated” (or made radioactive) by absorbing an additional neutron in the core
  - Hydrogen and Oxygen – produced when the neutron flux in the core breaks apart the water molecules
- These gasses do not condense in the condenser, and if not removed would create backpressure conditions that could lead to turbine damage

BWR Components

- So BWR operates with an **Offgas System** that takes a suction on the condenser to remove these gasses
- The hydrogen and oxygen exist in percentages that are explosive, so a catalytic **recombiner** is placed in the offgas stream to recombine some of these gasses to water for removal
  - The concentration of hydrogen in the offgas system is constantly monitored and could be a cause for plant shut-down
- The remaining gasses – some of which are radioactive – are passed at a slow rate through a series of charcoal beds. The charcoal “grabs” the gasses and traps them long enough for them to decay below the limits established for them to be released to the atmosphere

BWR Components

- Some plant transients require the isolation of the main Steam lines, to prevent the possible carry-over of radioactive materials
- This would normally leave the BWR without a means of decreasing the pressure and temperature in the vessel, leading to possible damage
- A series of **Safety Relief Valves** are installed before the main steam isolation valves. In the event the core is isolated, these valves direct the steam through a set of downcomers into a specially designed **Suppression Pool** below the reactor vessel where the steam can be condensed and pressure relieved


Secondary Containment
Drywell
Suppression Chamber (Wetwell)
Vent Line
Vent Header
Downcomer (Typical of 96)

Comparison

Plant Issue	BWR	PWR
Temperatures / Pressures	Relatively low, normal carbon steel components can be used	Higher pressures. Primary system components are more costly
Plant Design	All System Components contact radioactive materials – increased safety and cost issues	Only the primary systems contact radioactive materials – lower costs and no disposal issues
Reaction Control	Slow rate of power increase up to 70% - accomplished by slow withdrawal of control rods. 70 – 100% control much faster using jet pumps and altering core flow	Faster control of reaction using boric acid, but this has caused corrosion issues in the reactor vessels and Steam Generators

Nuclear Limitations

- Equipment Vibration
  - Individual component vibration is monitored by a central computer
  - Systems are quickly identified and isolated to prevent damage from excessive vibration
  - A problem area in nuclear plants are the protective relay panels
    - Excessive vibration may cause a system or plant shutdown due to vibration of relays
- Lengthy start-up times
  - Plants – especially BWR's – can require up to 3 days or more to reach full power output. A great deal of testing and "hold" points occur during power ascention

Nuclear Limitations

- With most plants operating on an 18 month or 2 year fuel cycle, the most intrusive maintenance work is done during the short (1-2 month) refueling cycles
- This means that a larger percentage of “routine” maintenance is done while the unit is operating
- Some maintenance activities create a “1/2-SCRAM” Signal due to operating some systems in a compromised manor
- A grid event may cause the second half of the SCRAM signal and cause a unit trip

Nuclear Limitations

- Plant operations are controlled by the **Nuclear Regulatory Commission (NRC)**. The plants must operate by their rules, as well as their license restrictions and individually written Technical Specifications (**Tech Specs**)
- **Tech Specs** specify the actions to be taken if any plant safety component is compromised or out of service. They may require a plant to reduce power, or even affect an immediate shutdown if certain conditions occur
- If a Plant experiences a SCRAM, the cause of the SCRAM must be determined and corrected before the plant can request permission to restart
- NRC permission must be obtained before the plant can be brought online

Hydroelectric Generation

Hydroelectric Generation

- Hydro once played a significant role in the electric utility industry accounting for 30%-40% of the total energy produced
- Currently, hydroelectricity produces about 10% of the electricity generated in America (about 3.5 % in PJM)
- Because the water cycle is an endless, constantly recharging system, hydro power is considered a renewable energy source
- Two types of hydroelectric generating plants:
  - Run of River
  - Pumped Storage

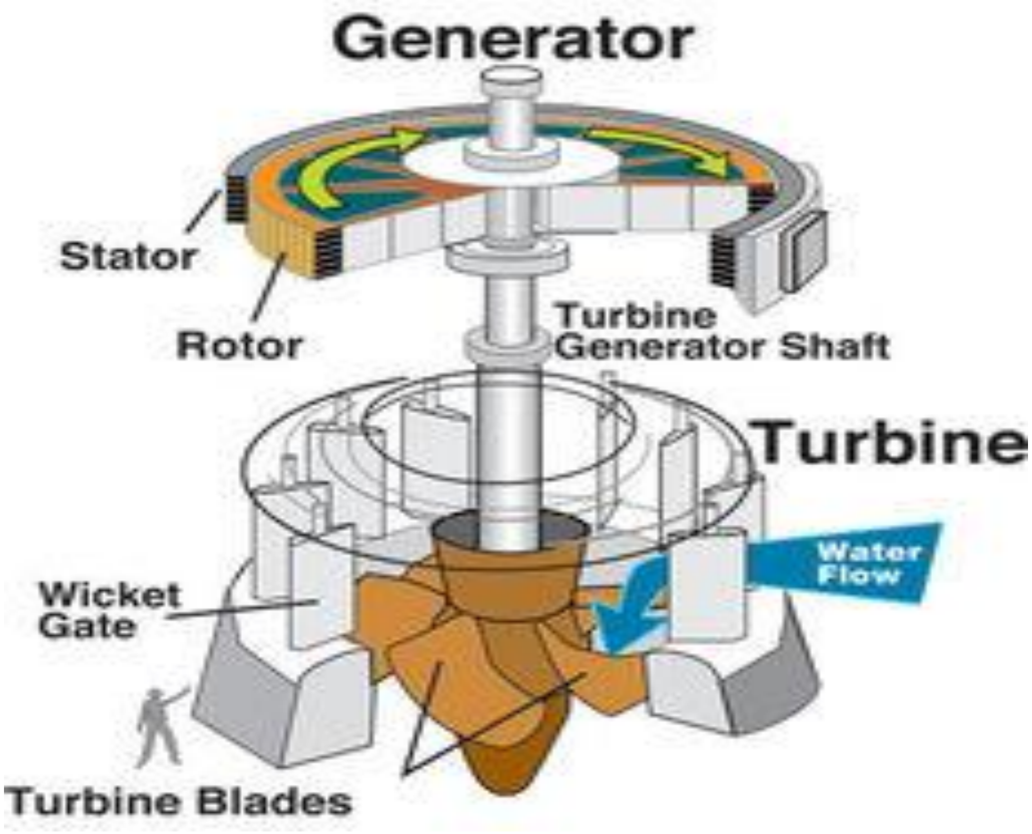
Hydroelectric Generation

- Basic design elements of hydro facility
  - Water at one elevation, and a dam or reservoir to hold it there
  - A lower elevation to which the water output can be directed
  - A Hydraulic turbine, connected to a generator
  - These plants convert the potential energy of the water to kinetic energy as it changes elevation, then to mechanical energy as it passes through the turbine, and then into electrical energy

Hydroelectric Generation

- Power capacity of a hydro plant is the function of two variables:
  - Flow Rate of the water (in cubic feet per second)
  - Hydraulic head – the vertical difference between the head water and tail water elevations
- Power output is controlled via the position of the **Wicket Gates**
  - These are adjustable vanes that control the amount of water that can enter the turbine. These are controlled by the governor by changing the angle of the gates

Hydroelectric Generation



Hydroelectric Generation

- Safety Considerations:
  - An Extra flywheel effect is built into the generator
    - dictated by the hydraulic conditions to prevent excessive rate of rise in speed if load is suddenly lost
    - Both Turbine and generator need to be built to stand :runaway" speeds due to the risk of a load loss when the gate-closing mechanism is inoperative
  - Generators at Hydro units are equipped with **Amortisseur Windings**. These windings;
    - Reduce overvoltage induced in the field caused by surges or imbalances in the stator
    - Reduce overvoltage in the stator caused by unbalanced faults in the machine
    - Aid in stability by reducing power output oscillations

Hydroelectric Generation

- Both Run-Of-River and Pumped Storage units offer:
  - Rapid start-up, shutdown and loading
  - Long life
  - Low operating and maintenance costs
  - Rapid response to changes in load/ frequency
  - Can be operated as a synchronous condenser for voltage control when not generating

Types of Hydraulic Turbines

- **Impulse Turbine**
  - Used in high head plants
  - Requires less water volume
  - Low velocity head is con-verted to a high velocity jet then directed onto spoon-shaped buckets
  - Less efficient at full load, but more efficient at partial load levels

Repair & Refurbishment of Pelton Wheel Runner - DP Test

Types of Hydraulic Turbines

- Advantages of an Impulse turbine:
  - Greater tolerance for sand/other particles in the water
  - Better access to working parts
  - No pressure seals needed around the shaft
  - Easier to fabricate and maintain
- Disadvantages of an Impulse turbine:
  - Unsuitable for low head sites because of low specific speeds

Types of Hydraulic Turbines

- **Reaction turbines**
  - Two types; Francis and Kaplan (Propeller)
  - Runner is fully immersed in water and enclosed in a pressure casing
  - Pressure differences impose lift forces, which cause the runner to rotate
  - Low to medium head is converted into high speed

Types of Hydraulic Turbines

- Advantages of a Reaction turbine:
  - Will rotate faster for the same head and flow conditions allowing for a more compact machine
  - Eliminates the need for a speed-increasing drive system
  - Simpler to maintain – less cost
  - Higher Efficiencies
- Disadvantages of a Reaction Turbine
  - Requires more sophisticated fabrication
  - Poor efficiency under partial flow conditions

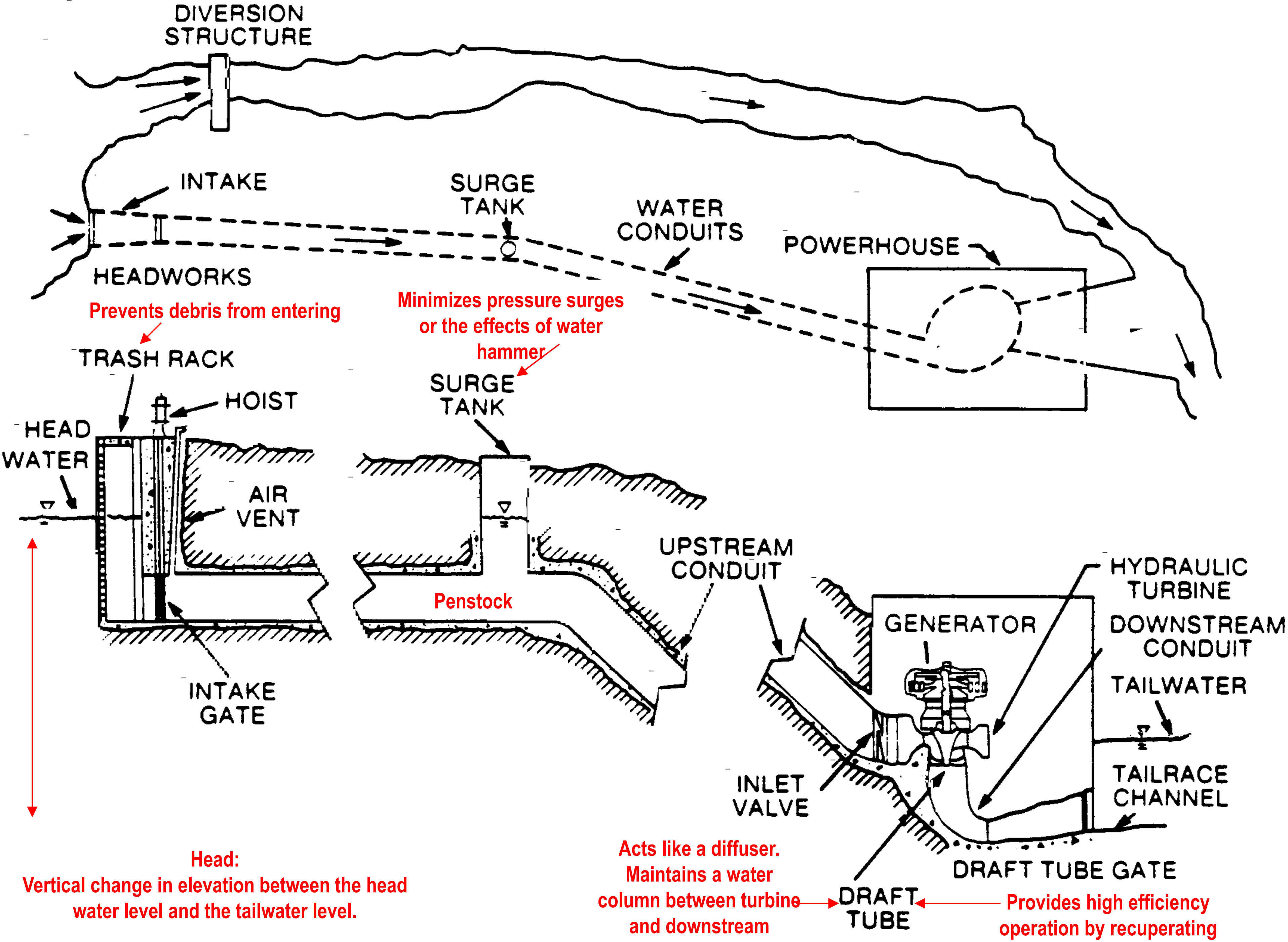
Run-of-River

Run-Of-River

- Low impact method that utilizes the flow of water within the natural range of the river, requiring little or no impoundment.
- Produce little change in the stream channel or stream flow
- Plants can be designed using large flow rates with low head or small flow rates with high head
- Advantages:
  - Reduced exposure to price volatility
  - Minimal construction
  - Ecologically sound
  - Reliable
  - Low operating costs

Run-Of-River

- Operating Considerations
  - Rainfall in the watershed area
  - River flow and Forebay/tailrace elevations
  - Water Quality impacts
    - Dissolved oxygen, temperature, increased phosphorous and nitrogen content
  - Icing problems during frigid temperatures



Prevents debris from entering

Minimizes pressure surges or the effects of water hammer

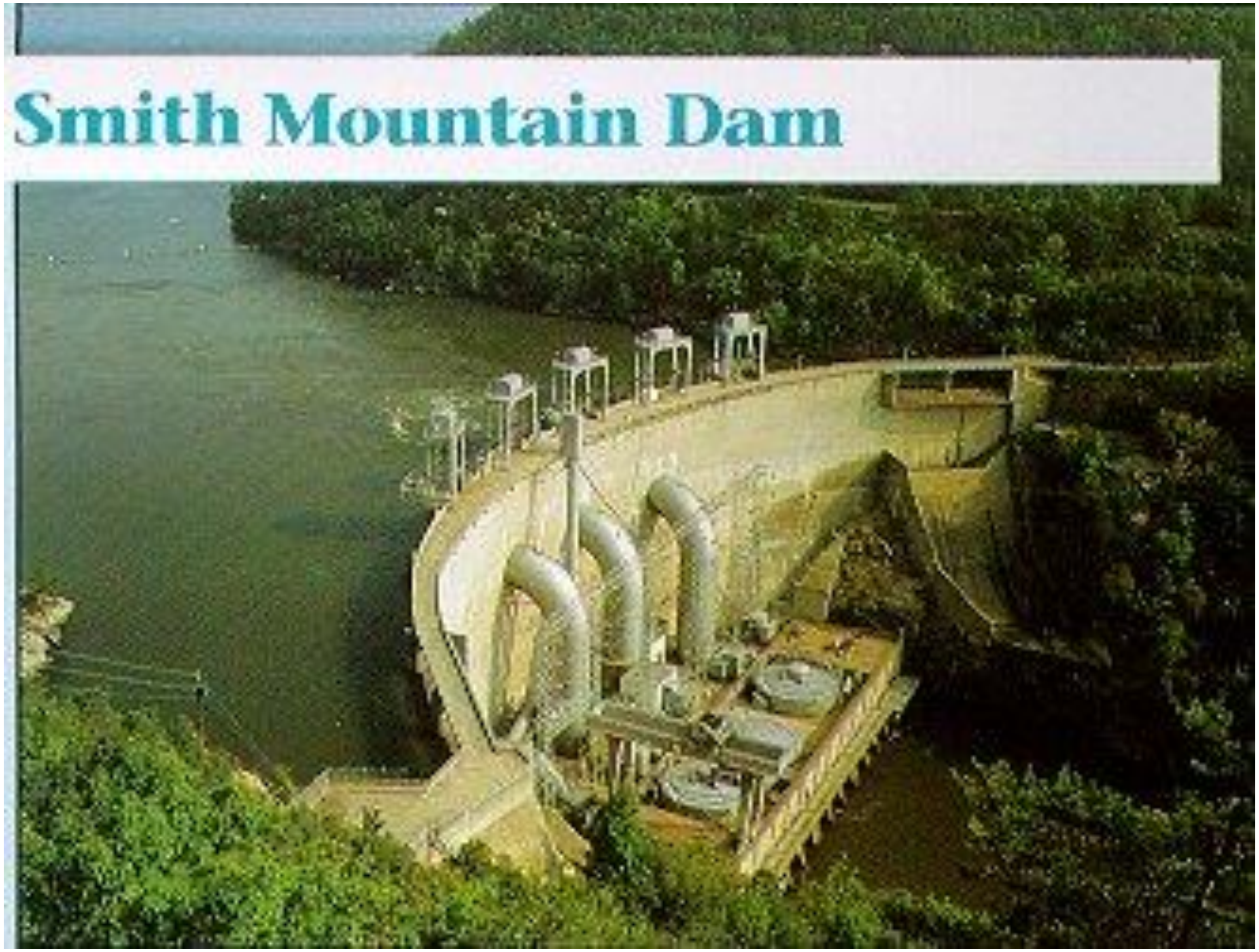
Penstock

Head:
Vertical change in elevation between the head water level and the tailwater level.

Acts like a diffuser. Maintains a water column between turbine and downstream

Provides high efficiency operation by recuperating kinetic energy

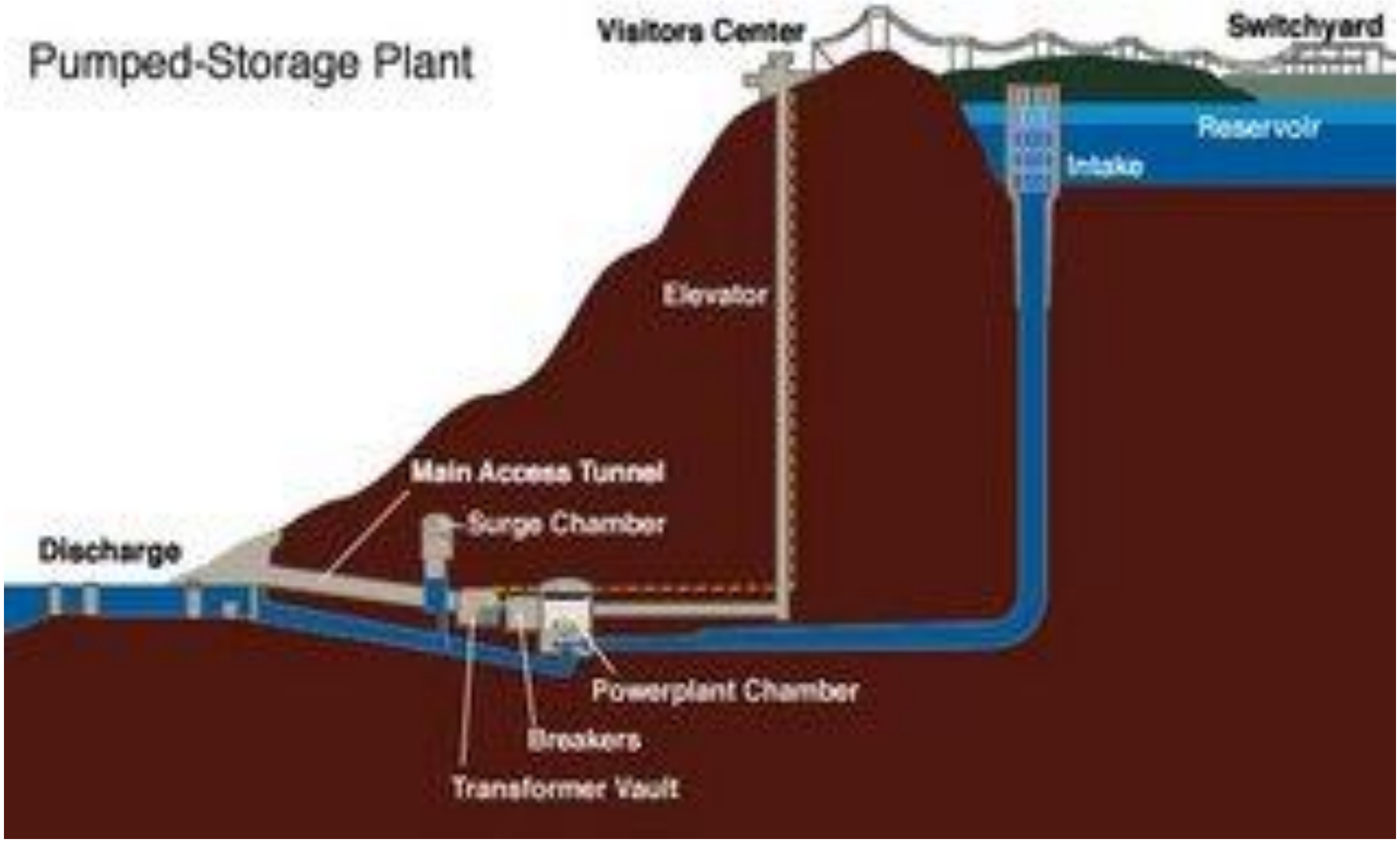
Pumped Storage



Pumped Storage

- Uses off-peak electricity to pump water from a lower reservoir to an upper reservoir
- During periods of high electrical demand, water is released to generate electricity
- Most modern plants utilize a reversible Francis-type turbine which operates in one direction of rotation as a pump, and the opposite direction as a turbine connected to a synchronous generator/motor driving the pump in one direction, and generating power in the other direction

Pumped Storage



Pumped Storage

- Operating Considerations
    - Water Quality impacts
        - Thermal stratification, toxic pollutants, Eutrophication (loss of nutrients)
    - Reservoir Sedimentation
    - Flood Control / Hazard
    - Effects on groundwater levels
    - Ice formation during cold periods

Combustion Turbine

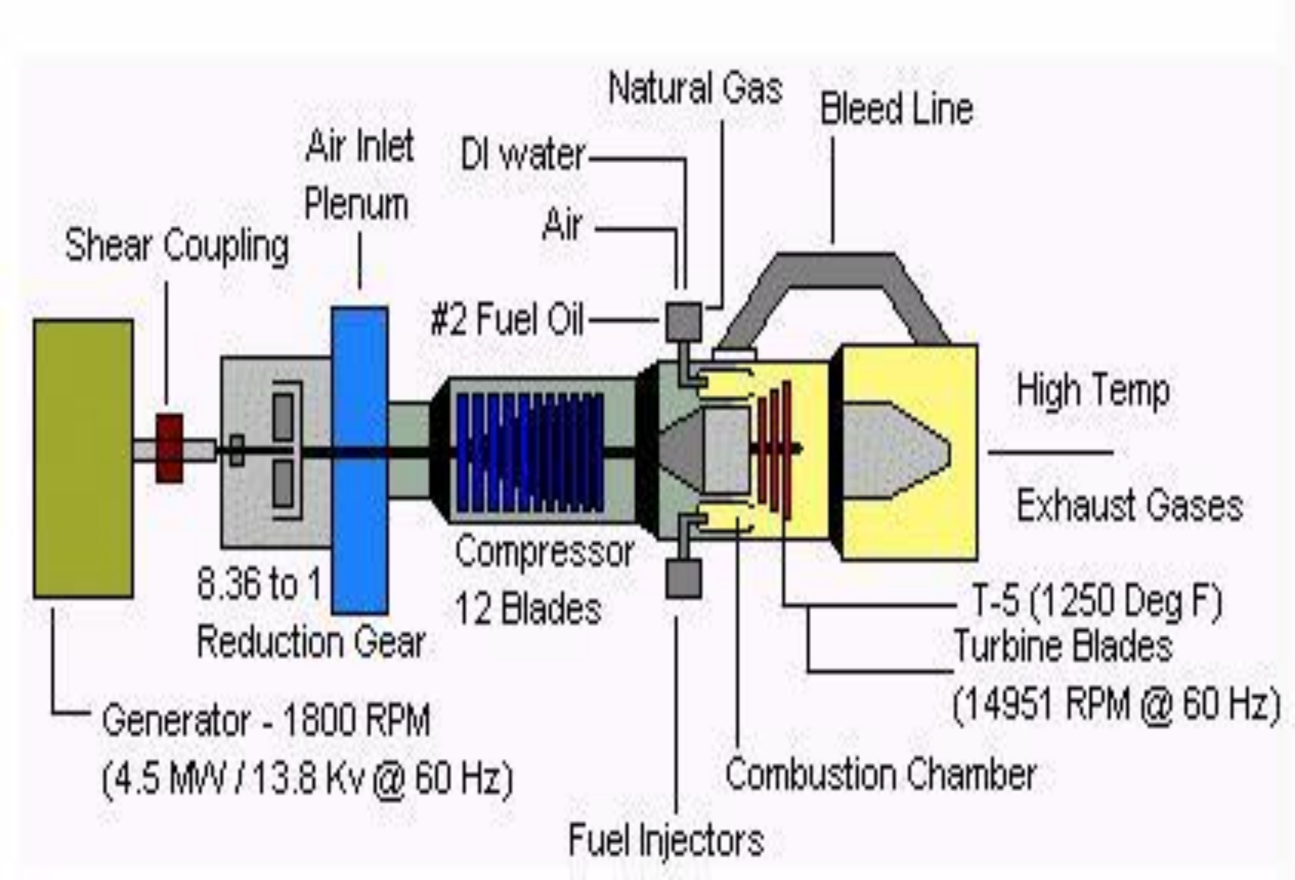
Combustion Turbines

- Combustion turbines play an important role in utility system generation planning
- Combined-cycle units provide most of the advantages of simple-cycle peaking plants with the benefit of a good heat rate; they also requires less cooling water than conventional fossil and nuclear of the same size
- We will examine both simple (single-cycle) and Combined Cycle CT’s

Simple-Cycle Combustion Turbines

- Operation is similar to a jet engine
- Air is compressed, mixed with fuel in a combustor, to heat the compressed air
- It is an internal combustion engine employing a continuous combustion process
- The turbine extracts the power from the hot air flow
- Connecting a generator to the turbine shaft creates electric power
- 2/3 of the produced shaft power runs the compressor; 1/3 produces the electric power
- Typical capacity – 15-180 MW

Combustion Turbine



Combustion Turbines

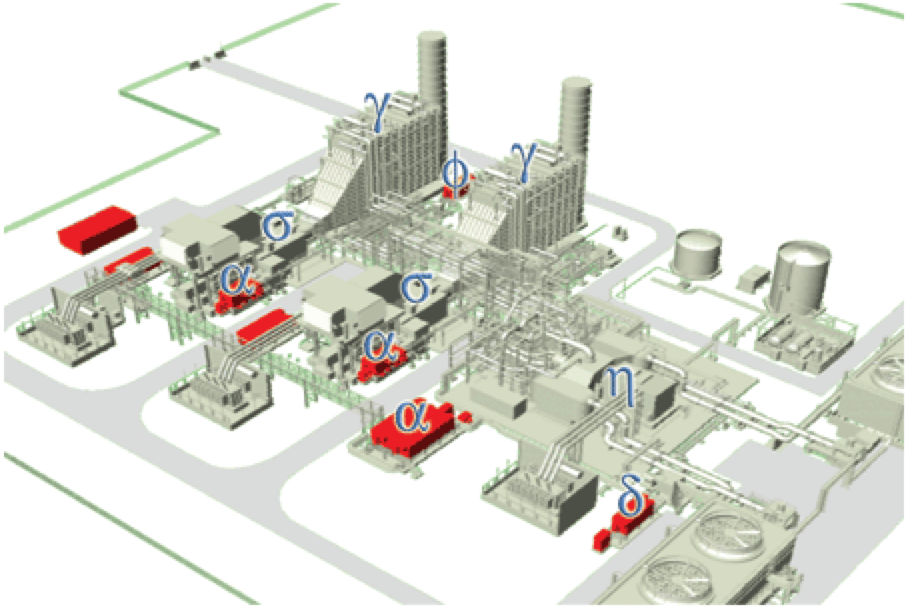
- **Advantages:**
  - Automatic- Some even have remote start capability (unmanned)
  - Low initial capital investment - turn-key operation (Modular)
  - Self contained unit
  - Short delivery time
  - Fast starting and fast load pickup
  - Very good Governor response
  - Some have Black Start capability
  - No cooling water required
- **Disadvantages**
  - Fuel operating cost (heat rate)
  - Low Efficiency: 25%- 40%
  - Thermal stress - High rate of temperature change, Short life due to cycling, High maintenance cost

Combustion Turbine

- CT MW Output Limitations:
  - Ambient air temperature & air density
    - Most efficient when using cold, dense air
  - Cold Weather starting problems
    - Lube oil Temperature
    - Moisture in the Fuel

- CT Environmental Limitations:
  - Stack Emissions (Nox/CO2/CO)
    - High operating temperatures in combustion section accelerates nitric oxide formation and emission
    - Particulate emissions can be high (especially older units) – Opacity
  - Noise level limitations

Simple Combined Cycle Unit



Simple Combined Cycle Unit

- One (or more) combustion turbine unit along with an associated generator

<u>AND</u>

- One Heat Recovery Steam Generator (HRSG) along with it’s own steam turbine

- http://www.youtube.com/watch?feature=player_embedded&v=jQ4yp_0Djvc

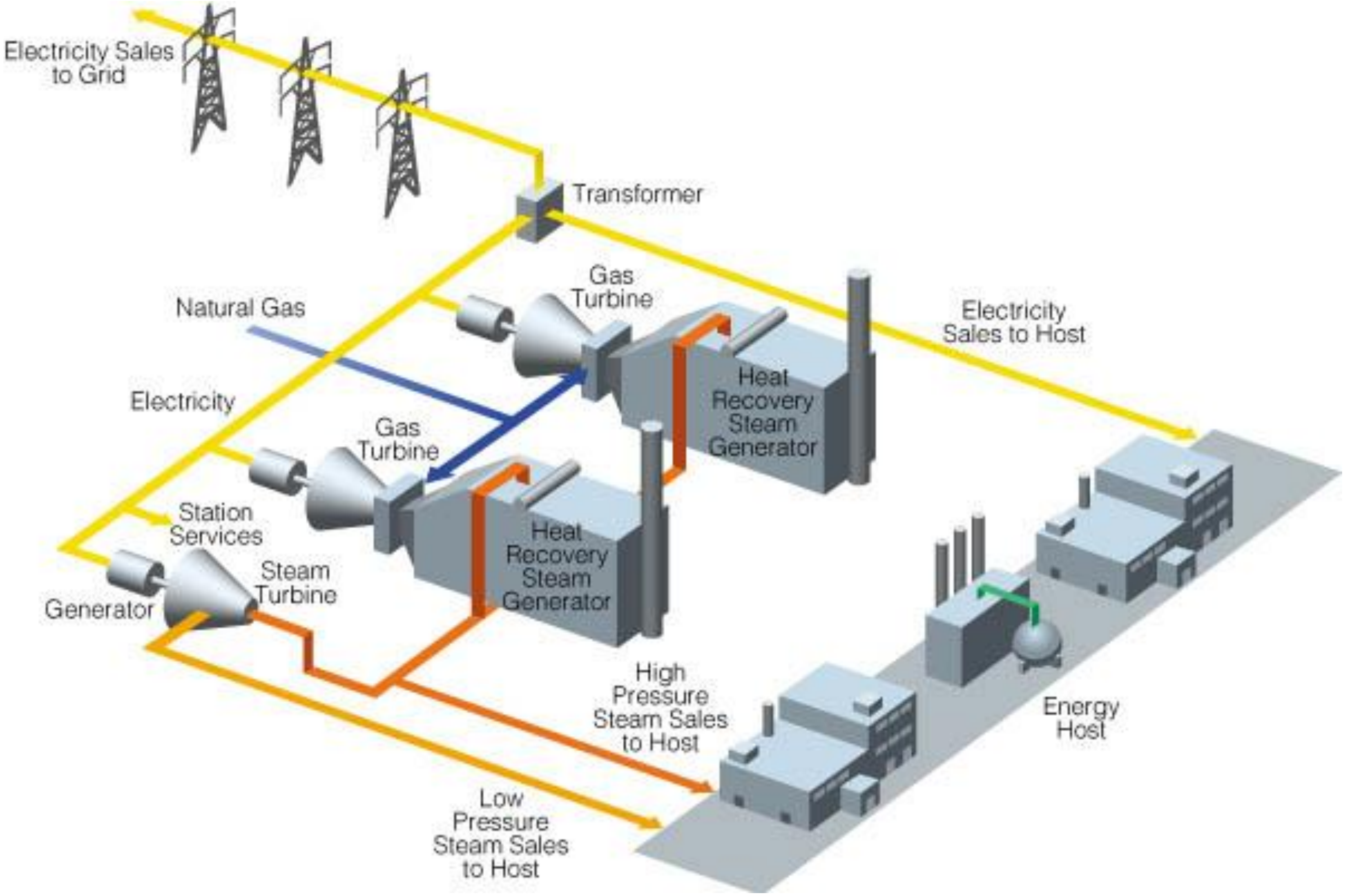
Combined Cycle

- The HRSG’s convert heat in the CT exhaust gas to steam for use in the steam turbine
- CT’s utilizing the HRSG can be operated from 50 to 100% peak load
- HRSG incorporates features of conventional fossil-fired boilers such as:
    - Economizer, Evaporator, and Superheater
    - Auxiliary systems for the steam turbine portion are similar to conventional steam plants
    - Cooling water must be supplied for the steam turbine’s condenser
    - Operates with a simple feedwater cycle

Combined Cycle and Co-Generation

- Combined Cycle units can be used in conjunction with Co-Generation
- Co-Generation (Distributed Generation)
  - A means of generating hot water, and / or high and low pressure steam and electricity at the same time, from the same energy source, yielding a highly efficient power plant

Combined Cycle with Cogeneration



Thermal Efficiency

Generation Type	Efficiency
Combustion Turbine	28% - 34%
Steam (no reheat)	31% - 35%
Steam (reheat)	36% - 41%
Combined Cycle	42% - 53%

Environment

- Gas fired Combined Cycle Unit Advantages
  - Lower Emissions
    - SO_2 and Particulate emissions are negligible
    - No_x emissions are lower than a conventional coal plant
    - No production or emission of sludge
    - No production or emission of ash
  - Land Use
    - CCPP on the average require five times less land than a coal fired plant (100 acres versus 500 acres)
  - Water Use
    - Lower cooling and condensate water consumption
    - Condensing steam turbine is only about 35% of output

Advantages/Disadvantages

- Disadvantages:
  - Increased chemistry requirements with more complex plants
  - Rapid heating and cooling of critical components
  - Emissions to the environment: nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO),carbon dioxide (CO_2), and opacity
  - Availability and cost of fuel
  - Poor thermal performance, high vibration, tube leaks, and ambient conditions
  - Auxiliary equipment out of service may prevent unit from achieving full load

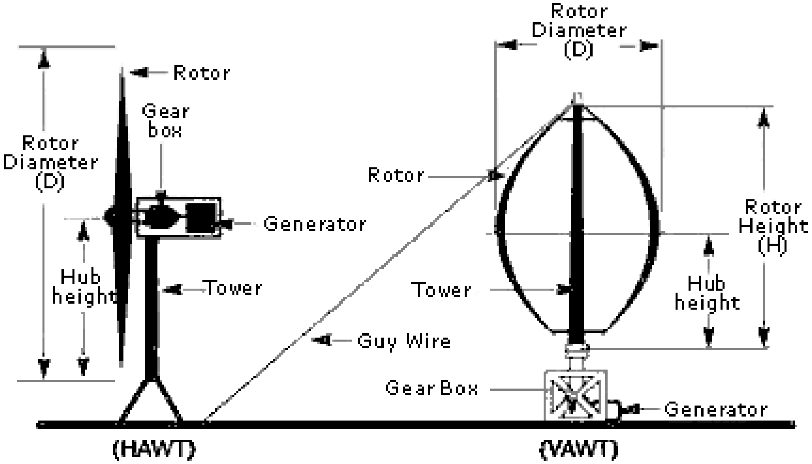
Wind Generation

Wind Generation

- Wind is a form of **solar** energy caused by:
  - Uneven heating of the atmosphere
  - Irregularities in the earth’s surface
  - Rotation of the earth
- Wind flow patterns can be effected by; terrain, vegetation, bodies of water
- Wind power turns kinetic energy of the wind into mechanical and electrical power
- Power available in the wind is proportional to the cube of its speed (Double the speed increases the power by a factor of eight)

Wind Generation

- Wind power depends on elevation and wind speed
- It is considered a free and renewable resource just like hydroelectricity
- Wind power currently provides roughly 1.5% of all electricity in PJM
- Two basic types:
  - Horizontal axis turbines
    HAWT
  - Vertical axis turbines
    VAWT



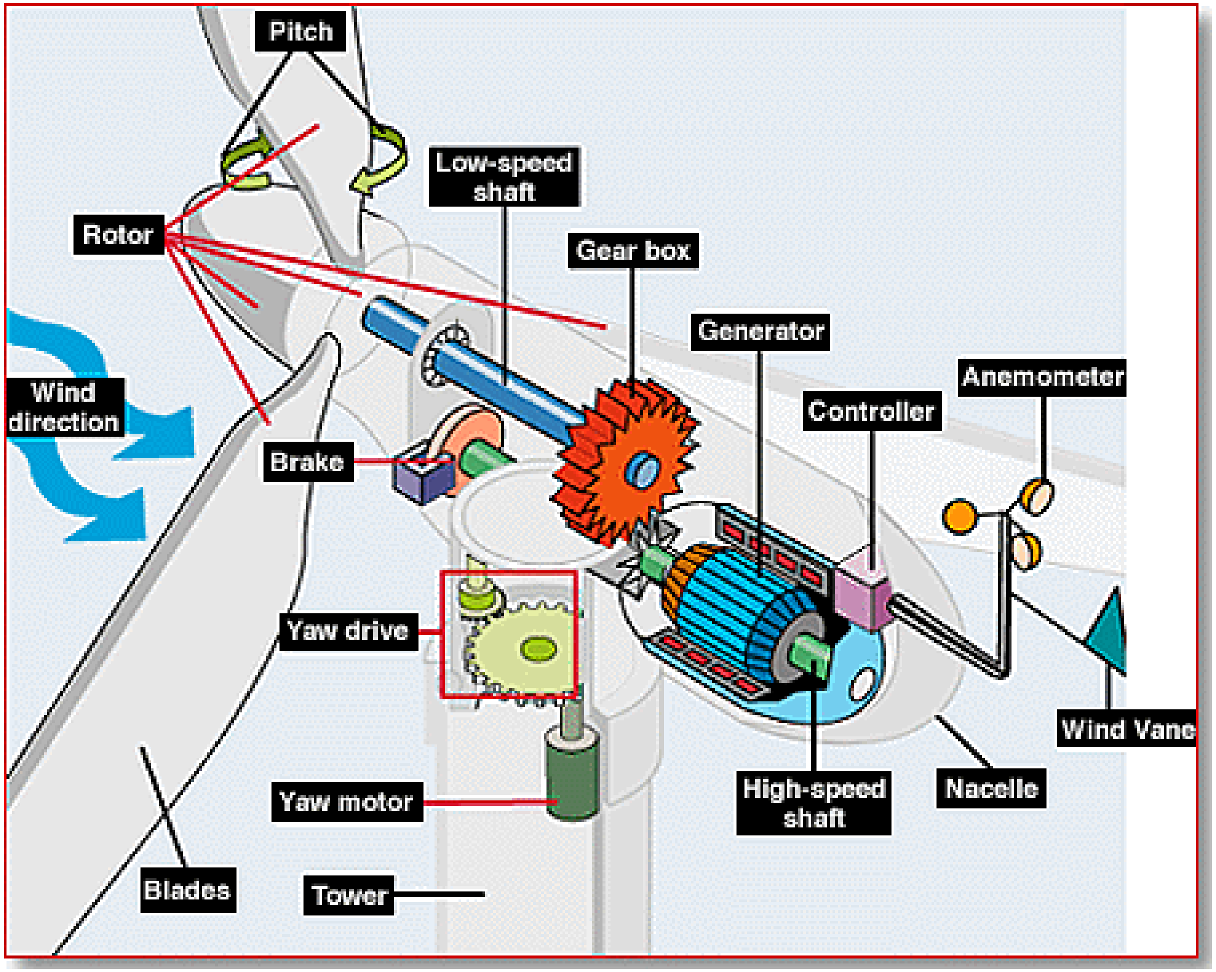
Wind Generation

- Wind Generators come in both:
  - **Asynchronous** – their speed is not locked in step with the grid
    - They produce power when the shaft of the generator is rotated faster than the synchronous frequency of the equivalent induction motor
    - Operate as Induction Generators -the magnetic field of the rotor is supplied from the grid via electromagnetic induction
  - **Synchronous**
    - Frequency of the rotor and stator magnetic fields generated by the coils are the same

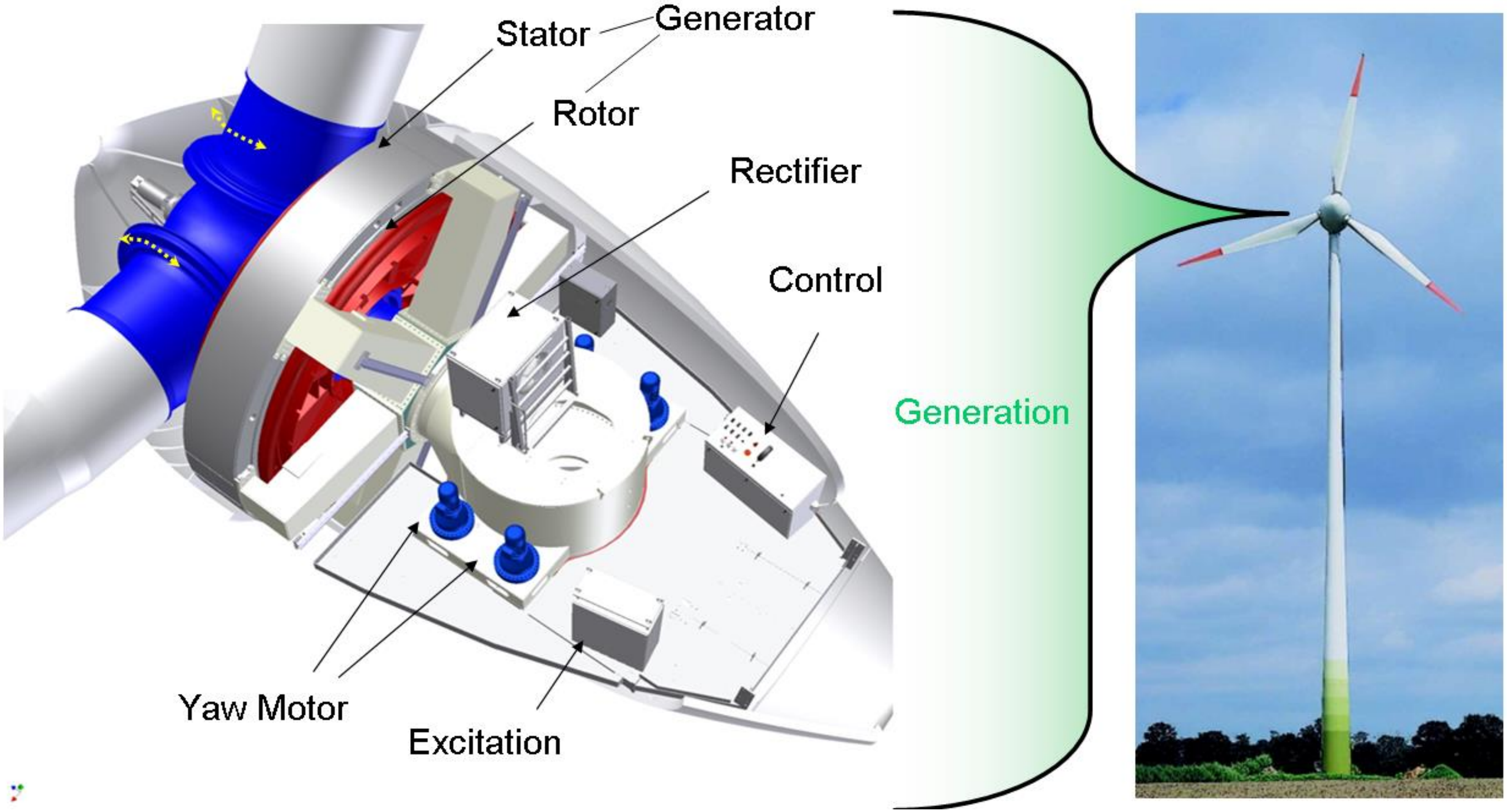
Induction Generator

- Induction generators:
  - Produce useful power at varying rotor speeds
  - Are simpler both mechanically and electrically than other types of generators
  - Do not require brushes or commutators
  - Are not self-exciting; require external excitation (reactive)
  - Require complicated electronic controllers (allows speed of the generator to vary with the speed of the wind)

Wind Power Generation



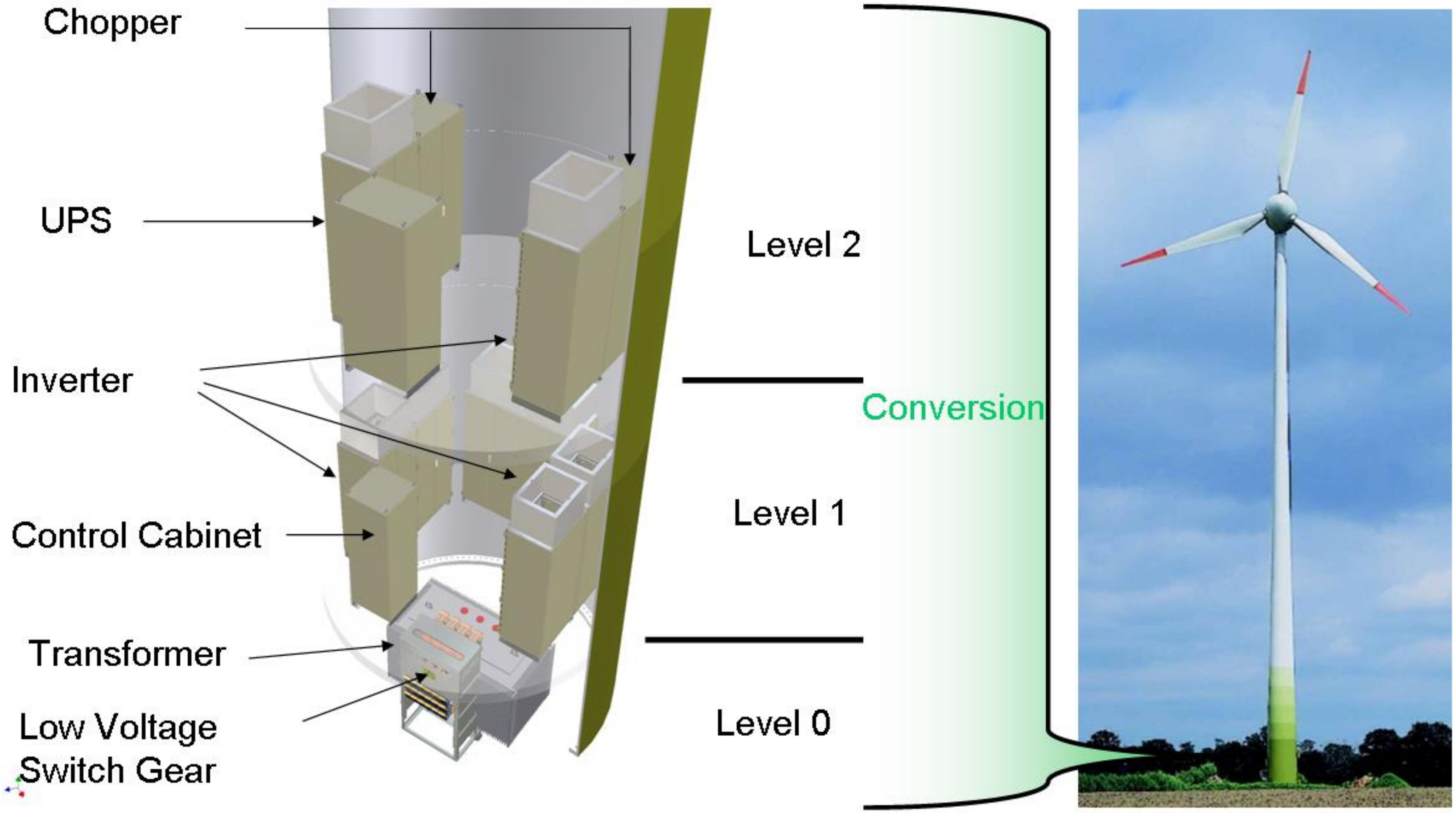
Wind Turbine Major Parts



Other type units may have gear boxes

Over the past decade, wind turbine use has increased at more than 25 percent a year

Tower Components



Wind Unit Components

- **Anemometer:** measures wind speed and transmits data to the controller
- **Blade:** catches the wind causing the blades to lift and rotate converting it to rotational shaft energy (2-3 blades)
- **Brake:** disc brake which can be applied mechanically, electrically, or hydraulically to stop the rotor in an emergency
- **Chopper:** circuitry used to obtain a controllable DC voltage from wind-driven, self-excited, pole-changing induction generators
- **Controller:** computer monitoring the turbine conditions such as overheating and power quality. It also starts the turbine, yaws it against the wind, and checks the safety systems
  - Starts at wind speeds of 8-16 mph
  - Shuts down at wind speeds greater than 55 mph

Wind Unit Components

- **Gearbox:** optimizes the power output connecting a low-speed shaft the high-speed shaft increasing rotational speeds from 30 to 60 rpm to 1,000 to 1,800 rpm
- **Generator:** induction-type producing 60 cycle AC
- **High-speed shaft:** drives the generator
- **Inverter:** converts incoming DC power into AC power for use on the Interconnection
- **Low-speed shaft:** connected to the rotor
- **Nacelle:** sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake
- **Pitch Control:** blades are turned out of the wind to control the speed of the rotor

Wind Unit Components

- **Rectifier:** converts incoming AC power into DC power for excitation
- **Rotor:** blade and hub assembly. Power available to the blades is proportional to the square of the diameter of the rotor
- **Tower:** tubular steel, concrete, or steel lattice. Taller the tower, more energy is captured; more electricity is generated
- **Yaw Control:** used by upwind turbines to rotate parallel to the ground to keep the rotor facing into the wind as wind direction changes

Wind Power Generation

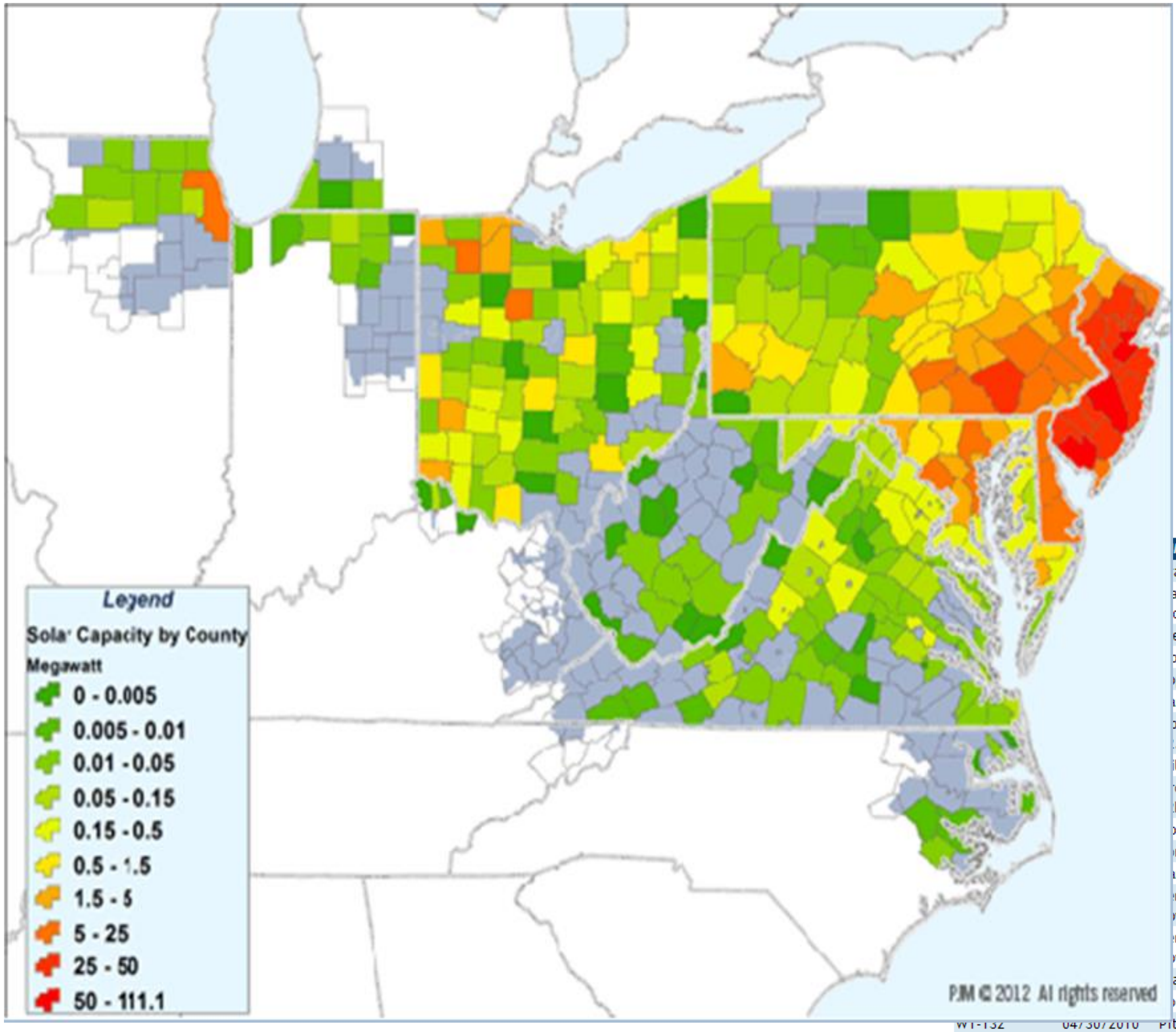
- Wind turbines are available in a variety of sizes
    - Largest has blades that span more than the length of a football field, stands 20 building stories high, and produces electric power for ~ 1400 homes
    - Smaller machines have rotors between 8 and 25 feet, standing ~ 30 feet, supplying an all-electric home or small business (usually below 100 kW)
    - Utility-scale turbines range in size from 100 kW to several megawatts

Wind Power Generation

- Wind Power Advantages:
  - Wind is a free, renewable resource
  - Non-polluting energy source
- Wind Power Disadvantages:
  - High initial Investment – 80% Equipment, 20% Site preparation
  - Intermittent resources at best
  - Remote locations
- Environmental Impacts
  - Noise produced by the rotor blades
  - Visual impacts on scenery
  - Wildlife effects

Solar Generation

Installed Solar Capacity within PJM RTO



PJM © 2012 All rights reserved

May 2012:
Installed Capacity > 1GW
16%-18% PJM Markets

Has doubled in each of last 2 years

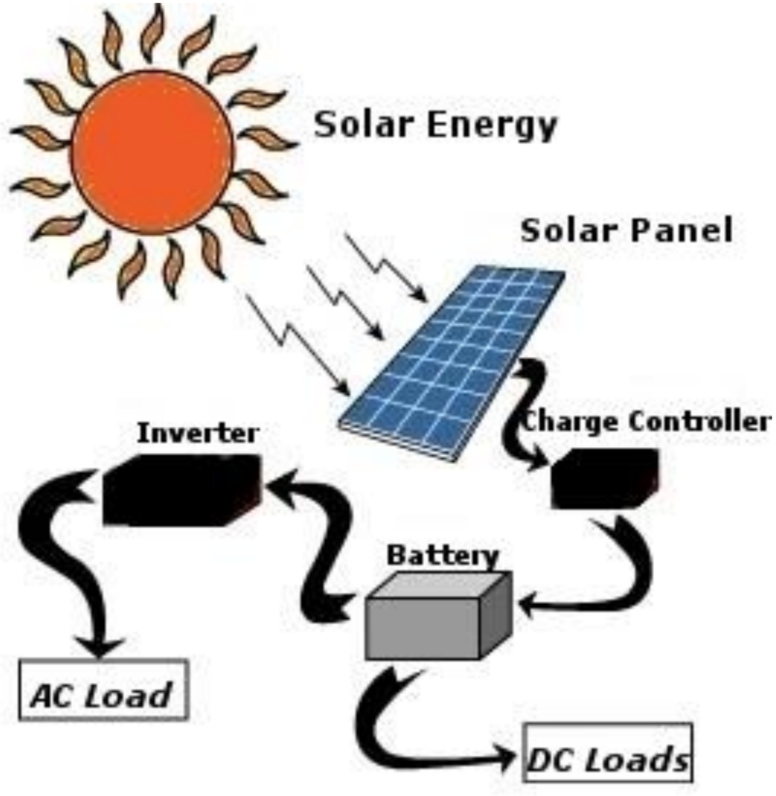
		M Substation	MW	MWC	MWE	Status	Feas	Imp	Fac	ISA	CSA	St	In Service	Fuel
		aynor 34.5kV	20	6.5	20	◇	●	●	⊗	⊗	⊗	NJ	2012 Q2	☼
		ainsboro & Devils ook 13kV	16	6.12	16.11	◇	●	●	⊗	⊗	⊗	NJ	2012 Q2	☼
		ewartsville 34.5kV	10	3.8	10	◇	●	●	⊗	⊗	⊗	NJ	2011 Q2	☼
		orris 34.5kV	10	3.8	10	◇	●	●	⊗	⊗	⊗	NJ	2013 Q4	☼
		pper Deerfield	10	3.8	10	◇	●	●	●	⊗	⊗	NJ	2014 Q2	☼
		arlisle Pike 23kV	5	2	5.3	◇	●	●	⊗	⊗	⊗	PA	2011 Q2	☼
		ontgomery Avenue .47kV	13	4.9	13	◇	●	●	⊗	⊗	⊗	PA	2012 Q2	☼
		ilford	0	7.6	20	◇	●	●	⊗	⊗	⊗	NJ	2014 Q2	☼
		rove City Road kV	2	0.74	2	◇	●	●	⊗	⊗	⊗	PA	2015 Q3	☼
		olmdel	4	1.52	4	◇	●	●	⊗	⊗	⊗	NJ	2013 Q1	☼
		rt Carbon	3	1.14	3	◇	●	●	⊗	⊗		PA	2013 Q4	☼
		amanend	3	1.14	3	◇	●	●	⊗	⊗		PA	2014 Q2	☼
		emberton ownship 1 12kV	0	6.8	18	◇	●	●	⊗	⊗	⊗	NJ	2013 Q4	☼
		emberton ownship 2 12kV	0	7.6	20	◇	●	●	⊗	⊗	⊗	NJ	2013 Q4	☼
		antage 12.47kV	5	1.93	5.13	◇	●	●	⊗	⊗	⊗	NJ	2014 Q4	☼
		ookstown 34.5kV	5	1.9	5	◇	●	●	⊗	●	●	NJ	2013 Q3	☼
W1-132	04/30/2010	Pittstown	2	0	2	◇	●	●	⊗	⊗	⊗	NJ	2014 Q2	☼
W2-016	05/25/2010	Frenchtown 34.5kV	15	5.7	15	◇	●	●	⊗	⊗	⊗	NJ	2014 Q2	☼
W2-026	05/28/2010	Glassboro Road	2	0	1.5	◇	●	●	●	⊗	⊗	NJ	2013 Q2	☼
W2-030	06/03/2010	Egg Harbor Township	10	3.65	9.6	◇	●	●	●	⊗	⊗	NJ	2014 Q1	☼
W2-040	06/29/2010	Camden 69kV	20	7.6	20	◇	●	●	⊗	●	●	OH	2017 Q2	☼
W2-060	07/29/2010	Burlington 26kV	20	7.6	20	◇	●	●	⊗	⊗	⊗	[illegible]	[illegible]	☼
W2-061	07/29/2010	Ringoes 12kV	3	1.1	3	◇	●	●	⊗	⊗	⊗	NJ	2014 Q2	☼
W2-073	07/30/2010	Fishburn/Tanney	4	1.52	4	◇	●	●				NJ	2014 Q3	☼

Projects: 118

Direct Solar Energy

- One step transformation to useable energy
    - Sunlight striking a solar cell by which electricity is immediately generated
    - Sunlight that is absorbed by the dark surface warms water in solar thermal collectors
    - Sunlight absorbed by a fiber optic cable that is fixed on the exterior of a building and lights the inside

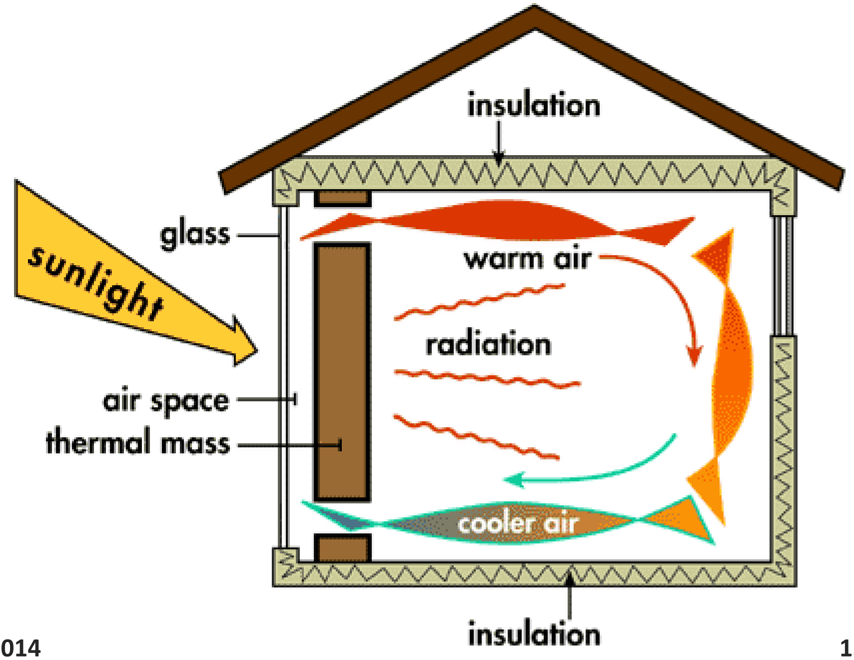
Direct Conversion into Electricity



- A silicon wafer with wires attached to the layers. Current is produced based on types of silicon used for the layers
- The absorbed light (photons) excites the electrons causing them to begin to flow in one direction
- Initially DC, later converted to AC
- Battery needed if storage is desired
- No moving parts, does not wear out
- Environmental conditions limit life to approx 20 years

Passive Systems

- Requires direct sunlight (only)
  - Sunlight warming an area through a window
  - Passive solar water heaters use no pump to circulate its water

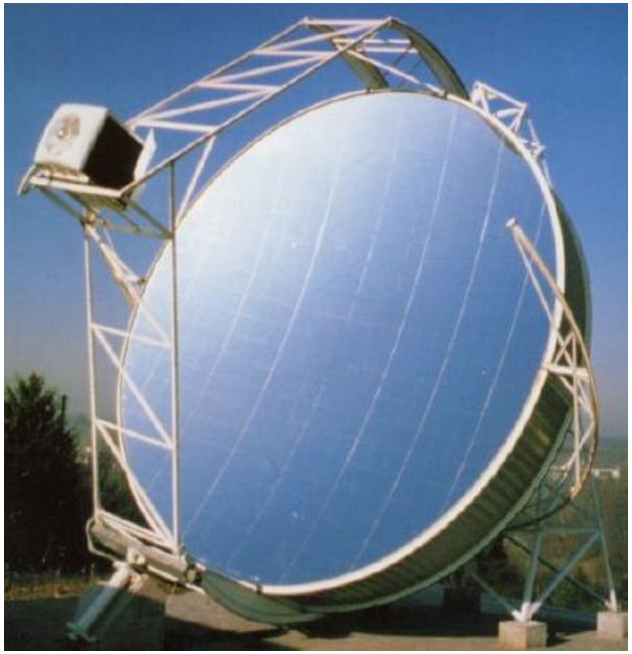


- A passively heated home uses about 60-75% of the solar energy that hits its walls and windows
- The Center for Renewable Resources estimates that in almost any climate, a well-designed passive solar home can reduce energy bills by 75% with an added construction cost of only 5-10%
- About 25% of energy is used for water and space heating

Active Systems

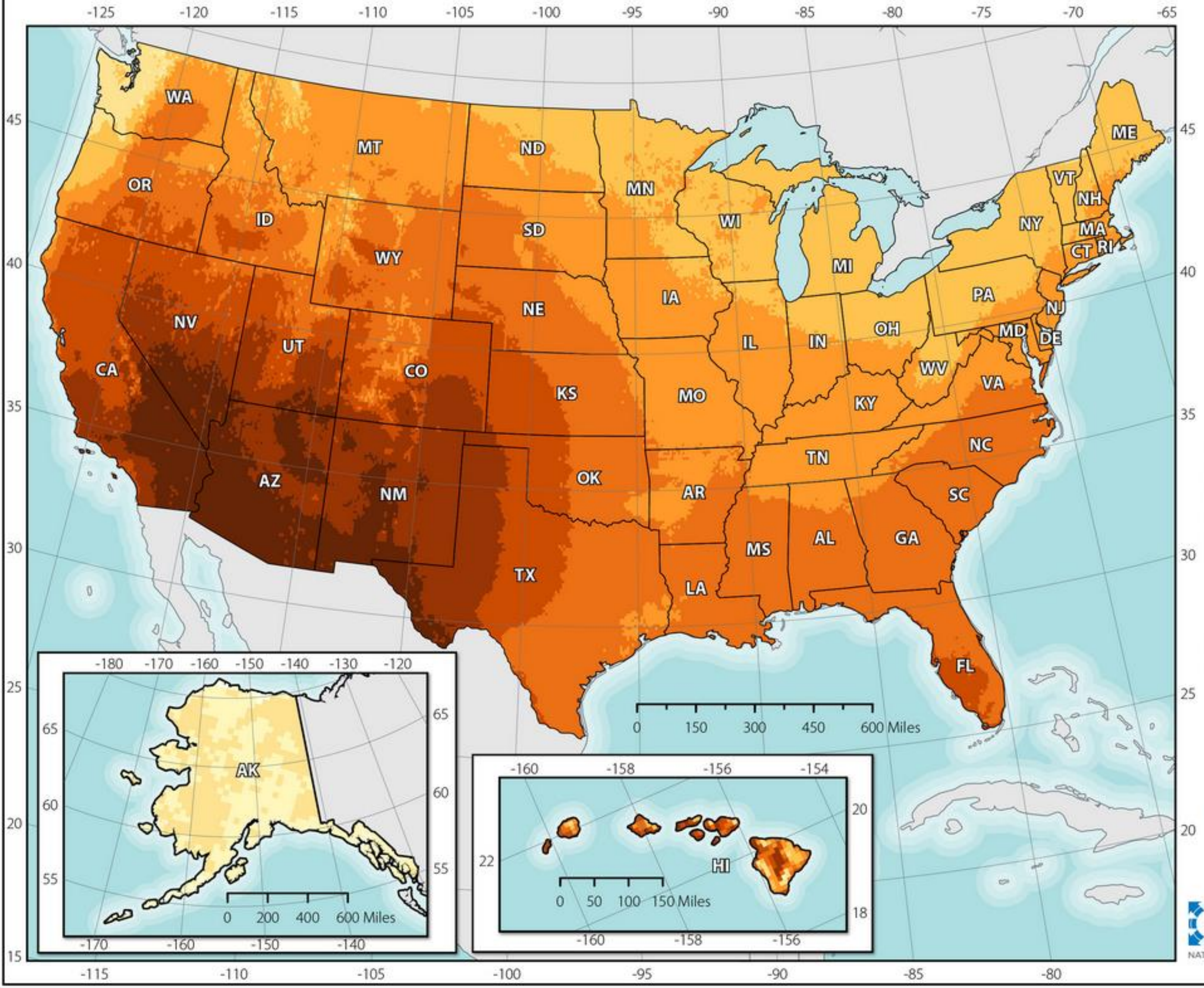
- Active systems use additional energy to make them work
  - Electronic tracking devices to maximize sunlight absorption electric pumps, air blowers, shutters, etc
  - Can be computer-controlled

Parabolic Dishes and Troughs



Solar-Thermal Electricity: Power Towers

Photovoltaic Solar Resource of the United States



kWh/m²/Day

- > 6.5
- 6.0 to 6.5
- 5.5 to 6.0
- 5.0 to 5.5
- 4.5 to 5.0
- 4.0 to 4.5
- 3.5 to 4.0
- 3.0 to 3.5
- < 3.0

Annual average solar resource data are shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states are a 10km satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2009.

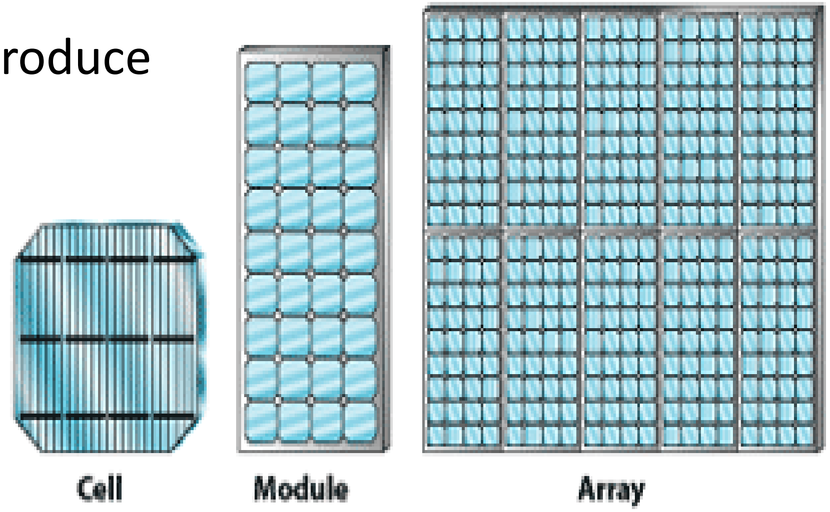
The data for Alaska are a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).

This map was produced by
the National Renewable
Energy Laboratory for the U.S.
Department of Energy.
Billy J. Roberts
19 September 2012

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

PV Systems

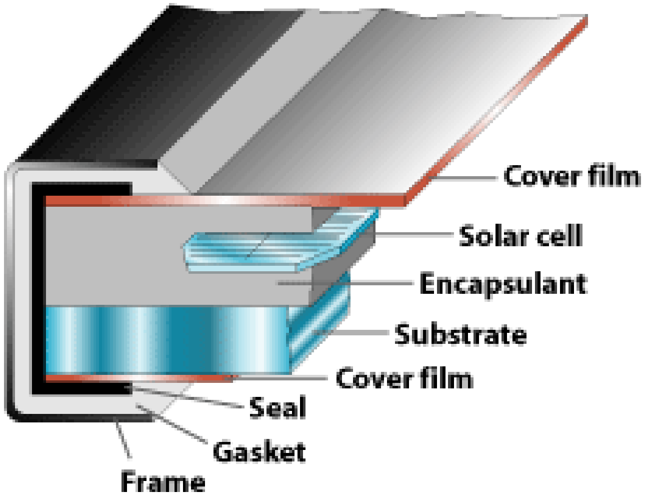
- Made up of several photovoltaic solar cells absorbing sun light, not warmth
  - Individual cells are small, typically producing about 1 or 2 watts of power
- Modules are groupings of individual cells
- Modules can be grouped together to form larger units called Arrays
- Arrays can be interconnected to produce more power
- PV systems are flexible and can meet almost any electric power need, small or large



Flat Plate Systems

- Most common photovoltaic (PV) array design
  - <u>Fixed position</u>
  - Moveable (track the movement of the sun)

- The simplest is a fixed position
  - Advantages
    - No moving parts
    - No additional equipment needed
    - relatively lightweight
    - suitable for many locations, including most residential roofs
  - Disadvantage
    - orientation to the sun is usually at an angle that is less than optimal
    - fixed arrays collect less energy per unit area of array than tracking arrays



One typical flat-plate module design uses a substrate of metal, glass, or plastic to provide structural support in the back; an encapsulant material to protect the cells; and a transparent cover of plastic or glass.

Summary

- Covered Elements of the Energy Conversion Process
- Provided an overview of:
  - Steam/Condensate/Feedwater and other Common Systems
- Described the various types of units:
  - Fossil generating units
  - Nuclear generating units
  - Hydroelectric generating units
  - Combustion turbines
  - Combined Cycle Power Plants (CCPP)
  - Wind Units
  - Solar Units

Questions?

Disclaimer:

PJM has made all efforts possible to accurately document all information in this presentation. The information seen here does not supersede the PJM Operating Agreement or the PJM Tariff both of which can be found by accessing: http://www.pjm.com/documents/agreements/pjm-agreements.aspx

For additional detailed information on any of the topics discussed, please refer to the appropriate PJM manual which can be found by accessing: http://www.pjm.com/documents/manuals.aspx