Power System Elements

Generating Unit Basics

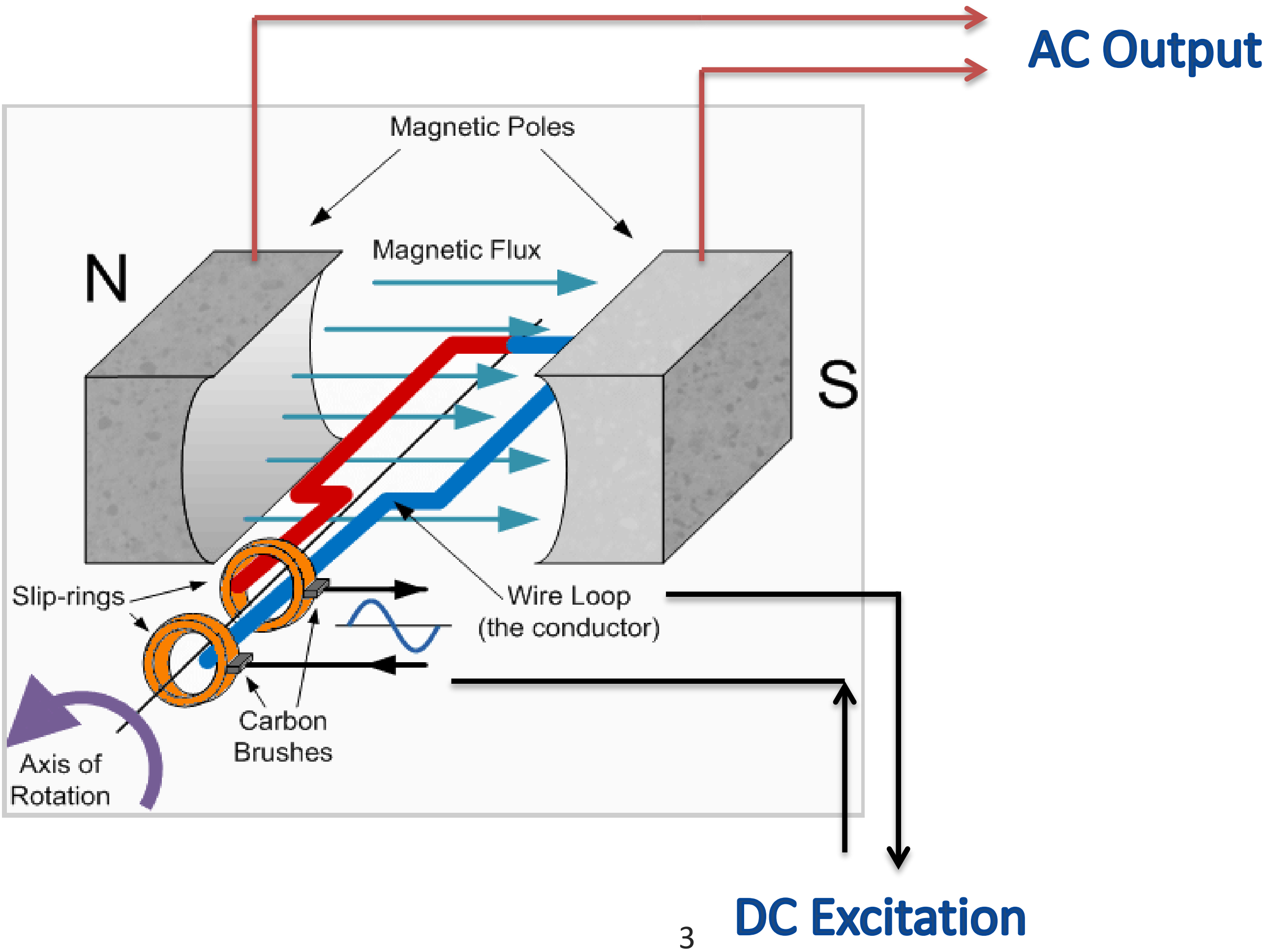
PJM State & Member Training Dept.

Objectives

- Provide an overview of:
  - Major components of a Generator
  - Excitation
  - Governor Control
  - Rotational Speed
  - Generator Limitations
  - VAR/Voltage Relationship
  - MWs and Power Angle

Basic Operating Principles

- ***Electromagnetic Induction*** is the principle used by a generator to convert mechanical energy into electrical energy

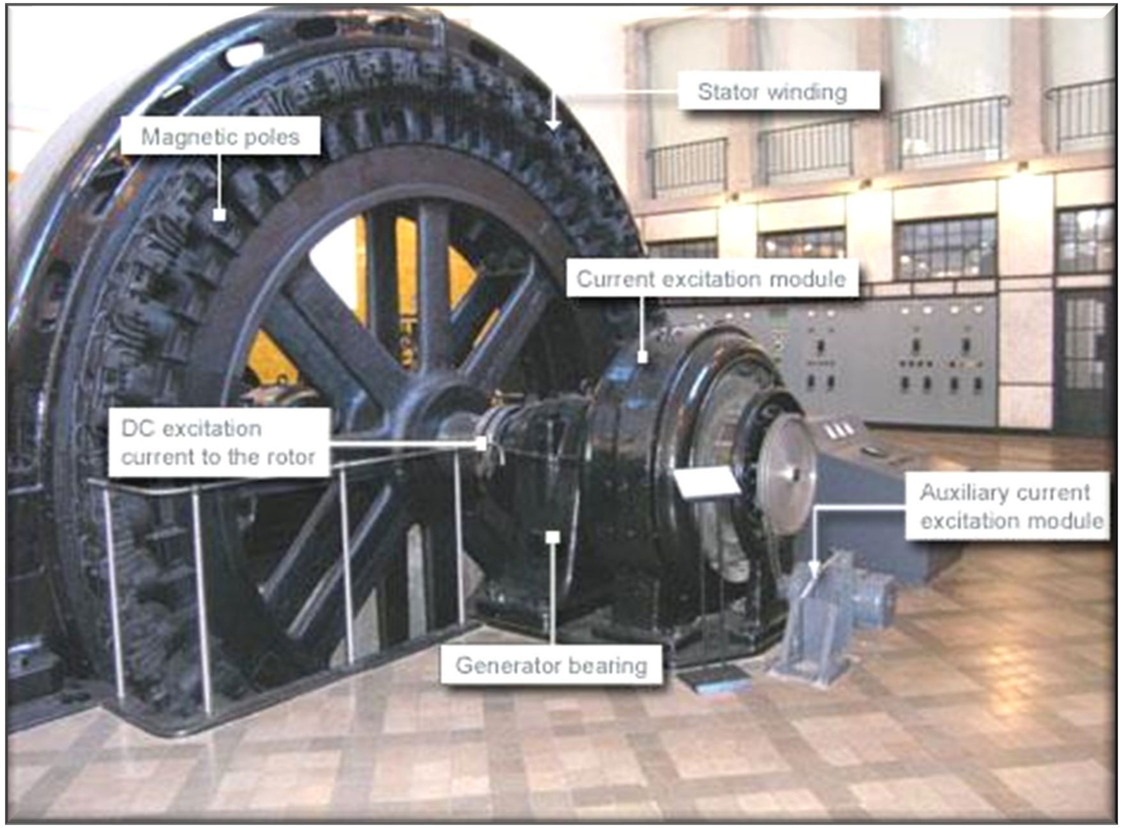


Basic Operating Principles

- Motion
  - Energy from the prime mover turns the generator rotor
- Magnet
  - Direct Current flows through the field windings of the rotor
- Wire
  - Spinning rotor induces a voltage in the windings of the generator stator

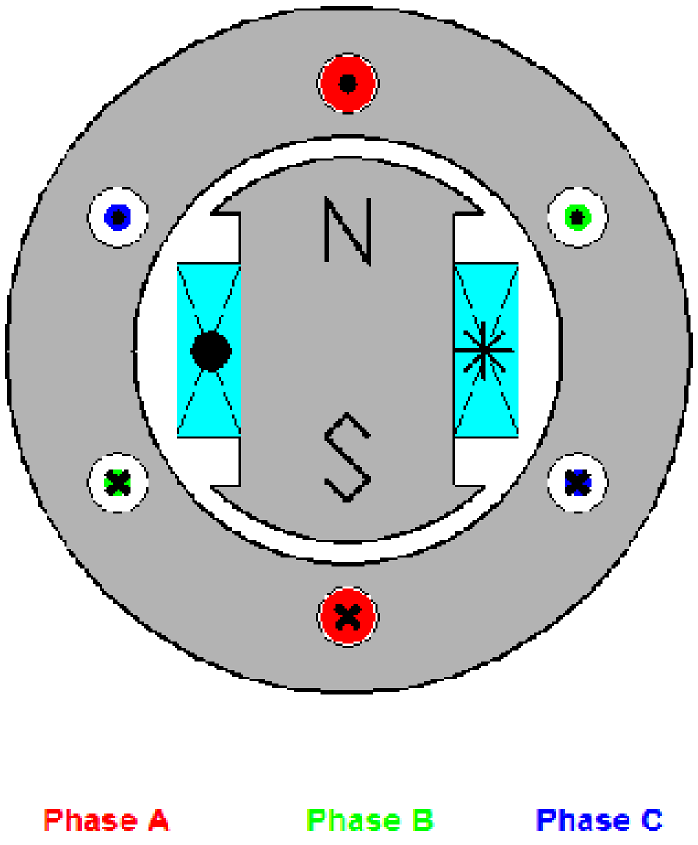
Basic Operating Principles

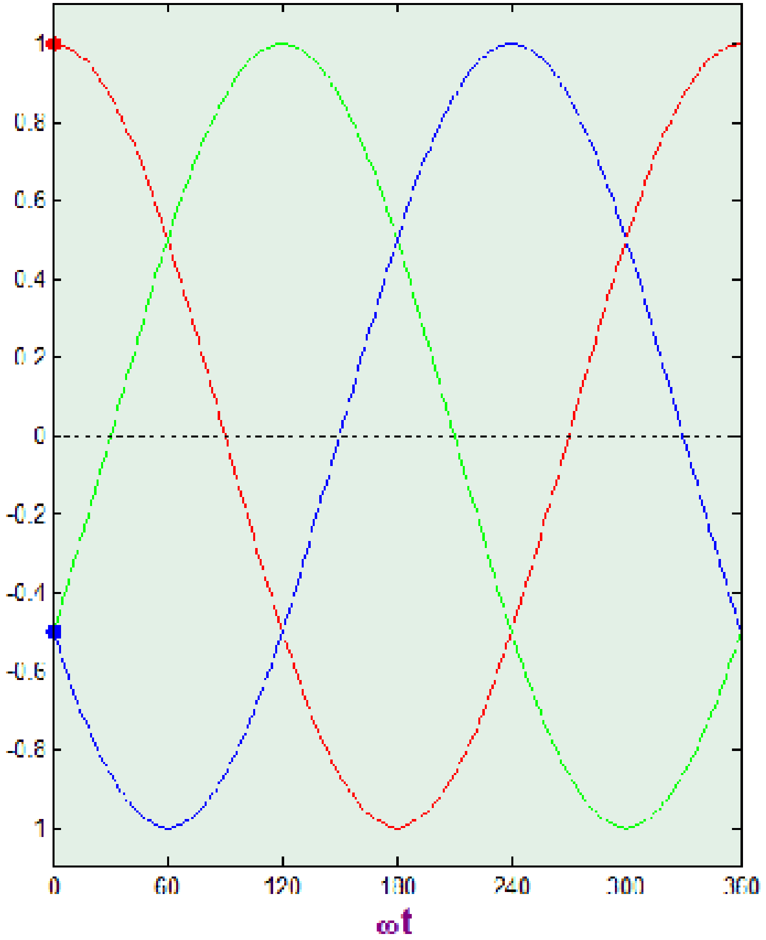
- **Direct current (DC)** or **excitation current** is supplied to the rotor's field winding by the **exciter**



Basic Operating Principles

Bismark Phasor Sim





A.C. Generator Components

- Rotating Magnetic Field (Rotor)
- Series of Stationary Conductors (Stator)
- Source of D.C. Voltage (Exciter)

Rotor

- Produces a magnetic field and induces an output voltage in the stator.
- The generated voltage is proportional to the:
  - Strength of the magnetic field
  - Number of coils and number of windings on each coil
  - Speed at which the rotor turns

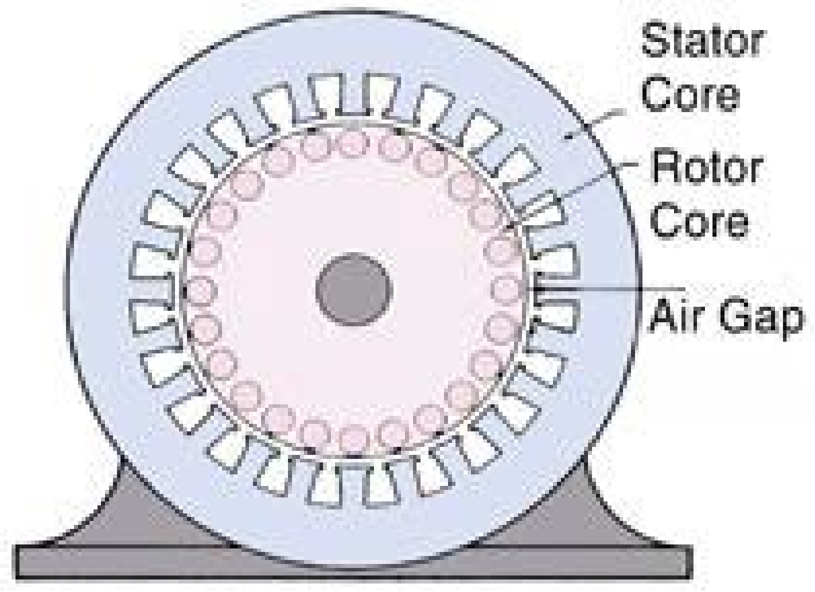
Rotor

- The rotating field is required to produce a given number of lines of magnetic flux which is obtained by: **Ampere-turns**

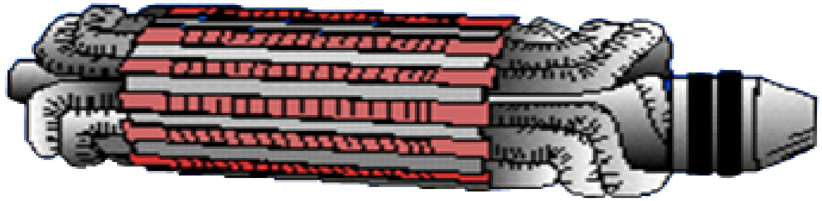
- Ampere-turns is the product of the number of turns in the rotor winding and the current that flows in the winding

Rotor

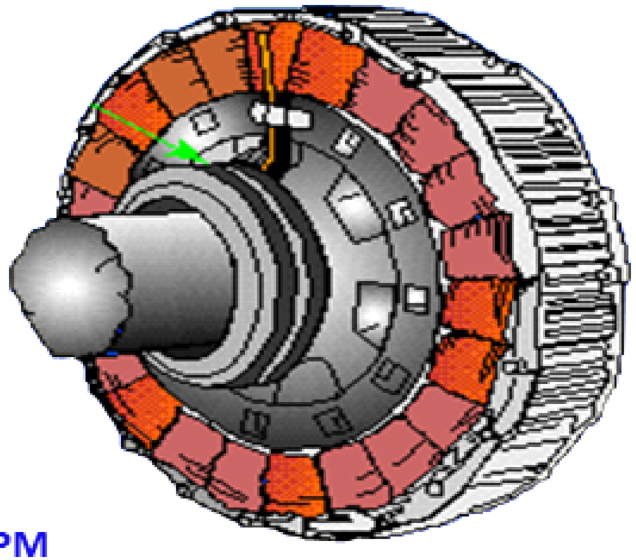
- Made of solid steel forgings with slots cut along the length for the copper windings
- Insulated winding bars are wedged into the slots and connected at each end of the rotor and are arranged to act as one continuous wire to develop the magnetic field



Rotor



SLIP RINGS



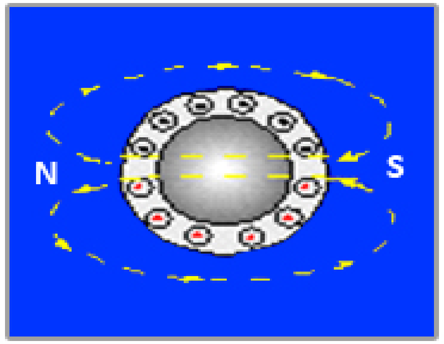
TURBINE DRIVEN ROTOR

HIGH SPEED = 1200 RPM OR MORE

SALIENT-POLE ROTOR

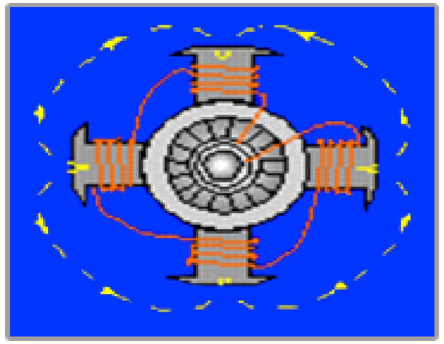
LOW SPEED = 1200 RPM OR LESS

CROSS - SECTION



LINES OF MAGETIC FORCE

SCHEMATIC



Rotor

- Rotor design constraints include:
  - Temperature:
    - Ampere-turn requirements for the field increase with an increase in rating, which entails a combined increase in heating in the coil
  - Mechanical force:
    - Ampere-turn requirements for the field increase with an increase in rating causing a higher centrifugal load
  - Electrical insulation:
    - In older units, slot insulation is a primary thermal barrier, and as current increases, becomes a greater obstacle

Rotor

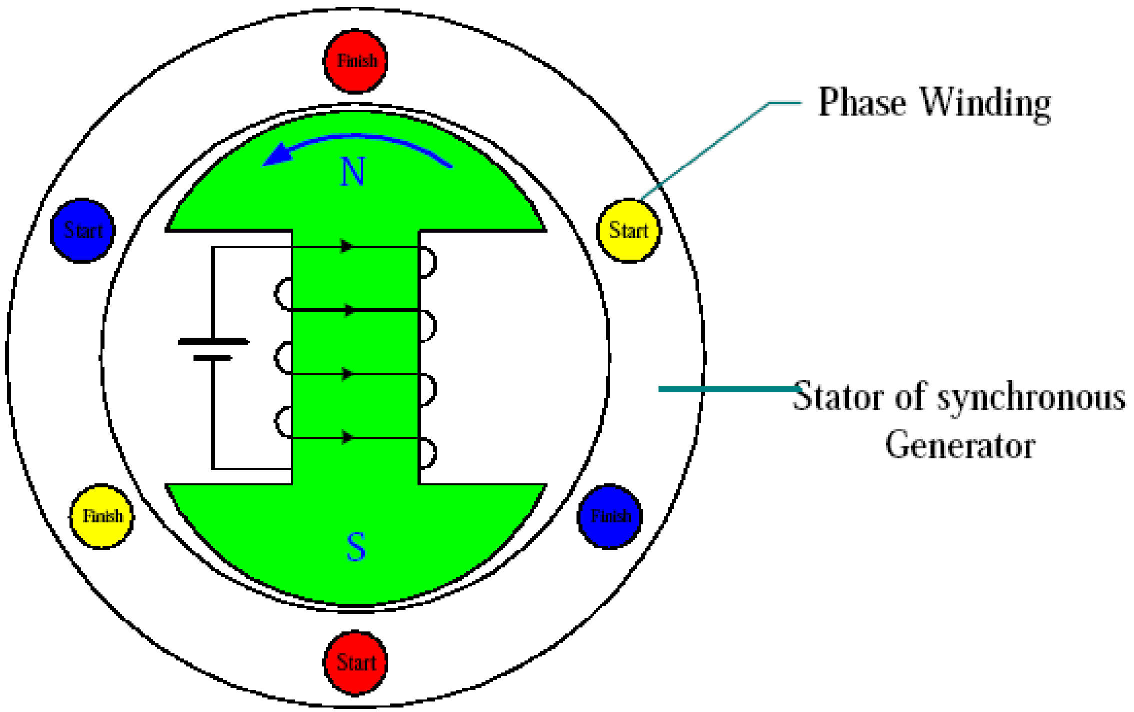
Advantage:

- Air gap between the stator and rotor can be adjusted so that the magnetic flux can be sinusoidal including the waveform

Disadvantage:

- Because of its weak structure it is not suitable for high-speed generation
- It is also expensive to fabricate
- Requires damper windings to prevent rotor oscillations during operations
- Due to low speed, they are constructed with a higher number of poles to achieve system frequency

Salient Pole Three Phase Synchronous Generator



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Rotor

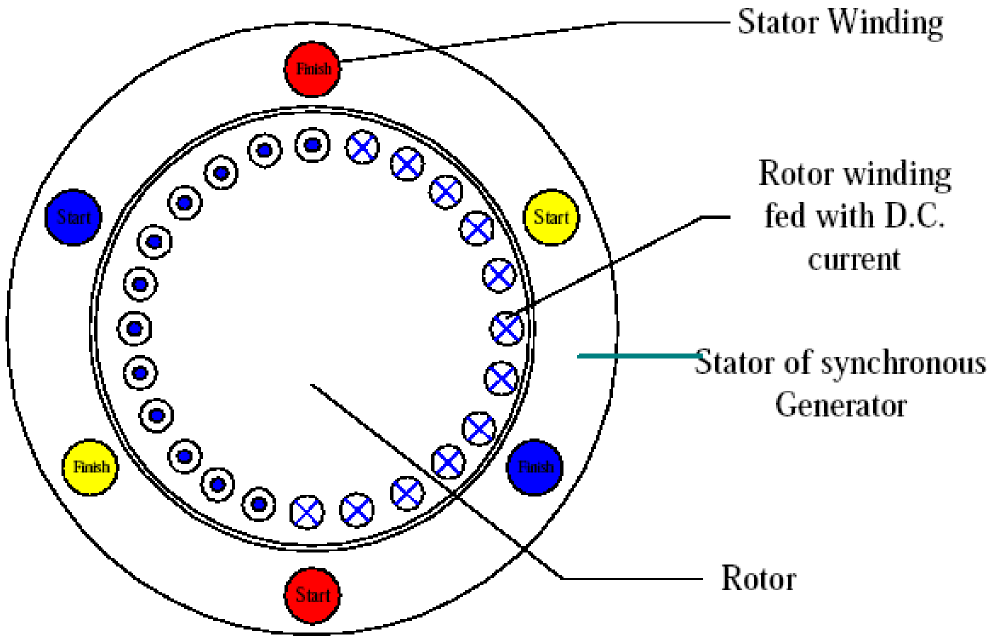
Advantage:

- Cheaper than a salient-pole
- Its symmetrical shape, is better for high-speed application
- Losses in the windings are reduced
- Noise produced is less

Disadvantage:

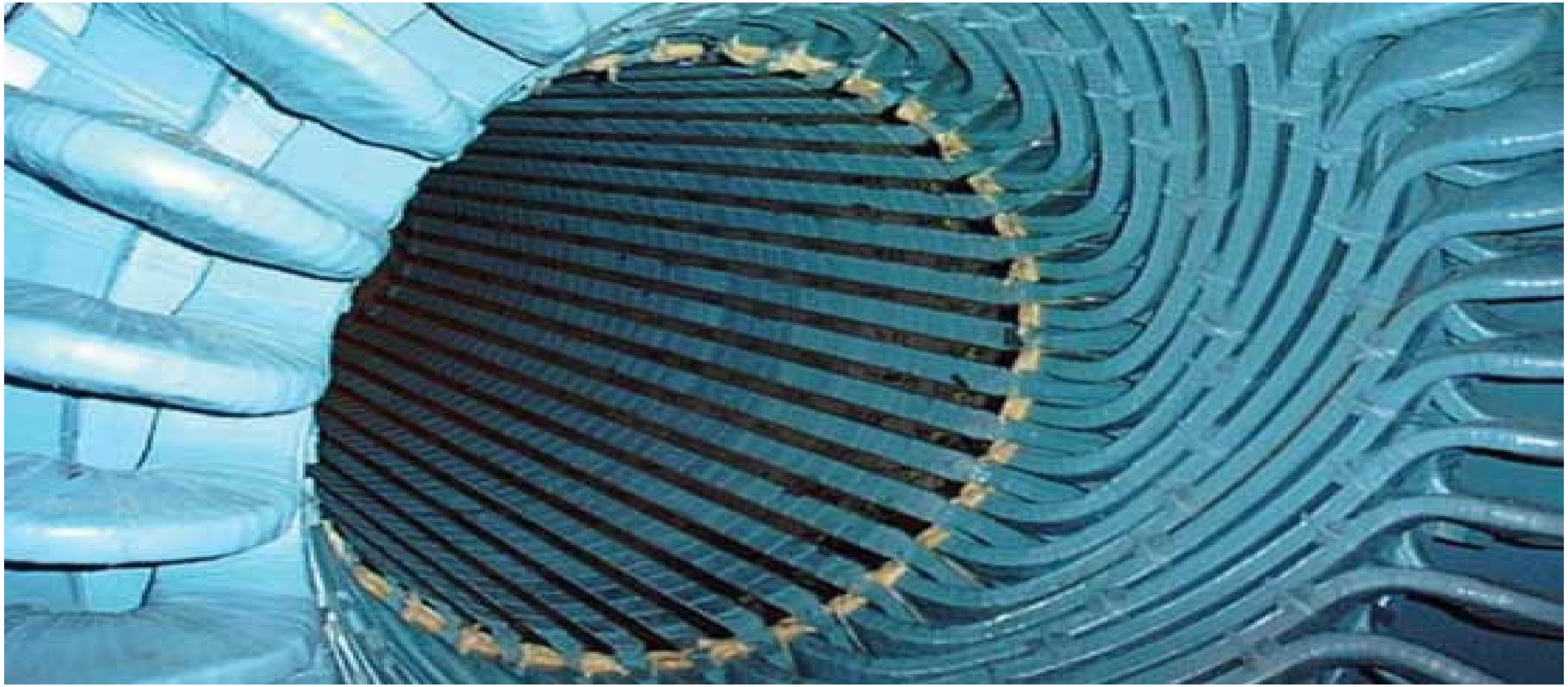
- Air gap is uniform
- Generated voltage is polygonal giving way to the susceptibility of harmonics

Cylindrical Rotor Synchronous Generator



Stator

- The frame assembly of the generator is the main component of the stator
- Insulated windings or coils are placed in slots near an air gap in the stator core



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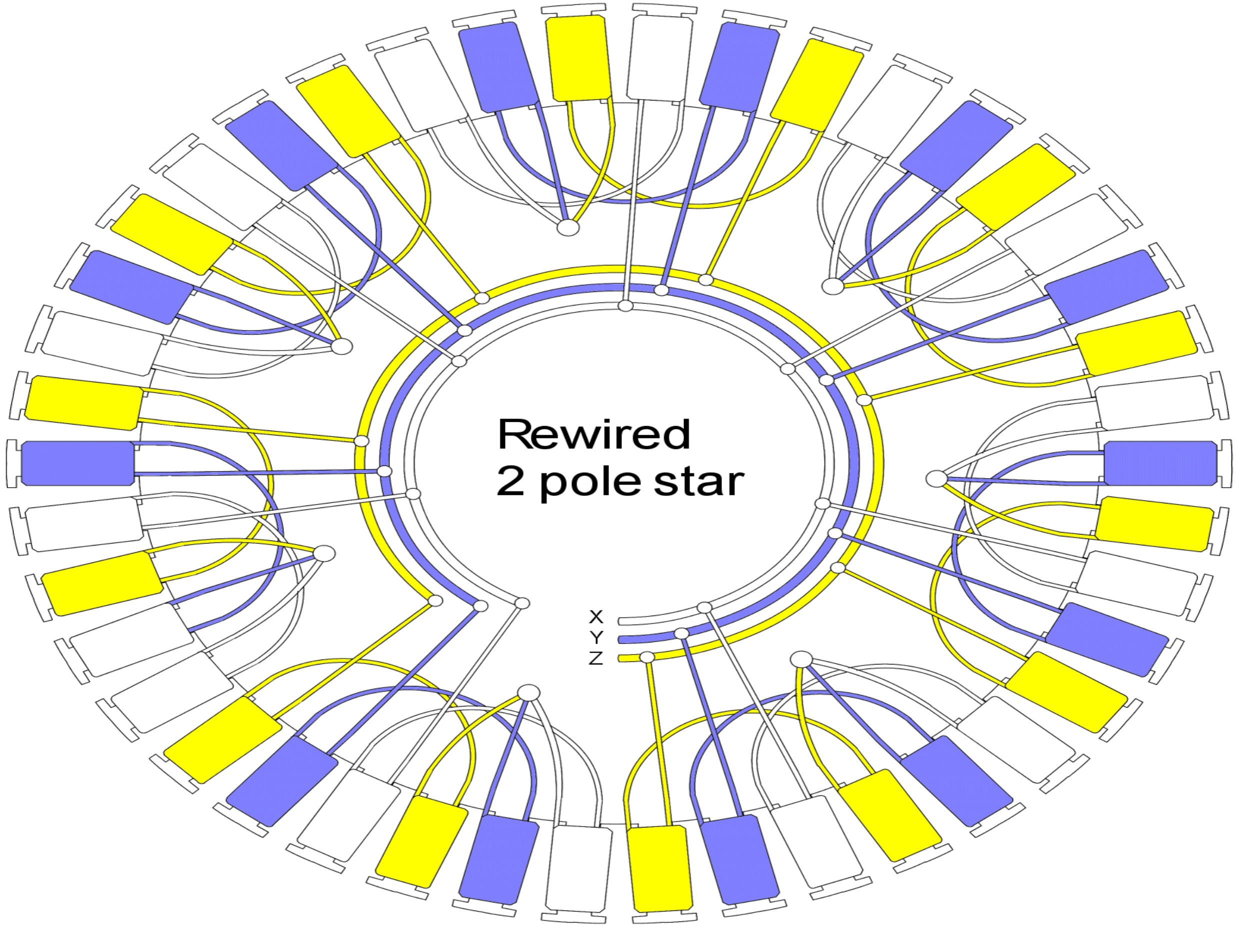
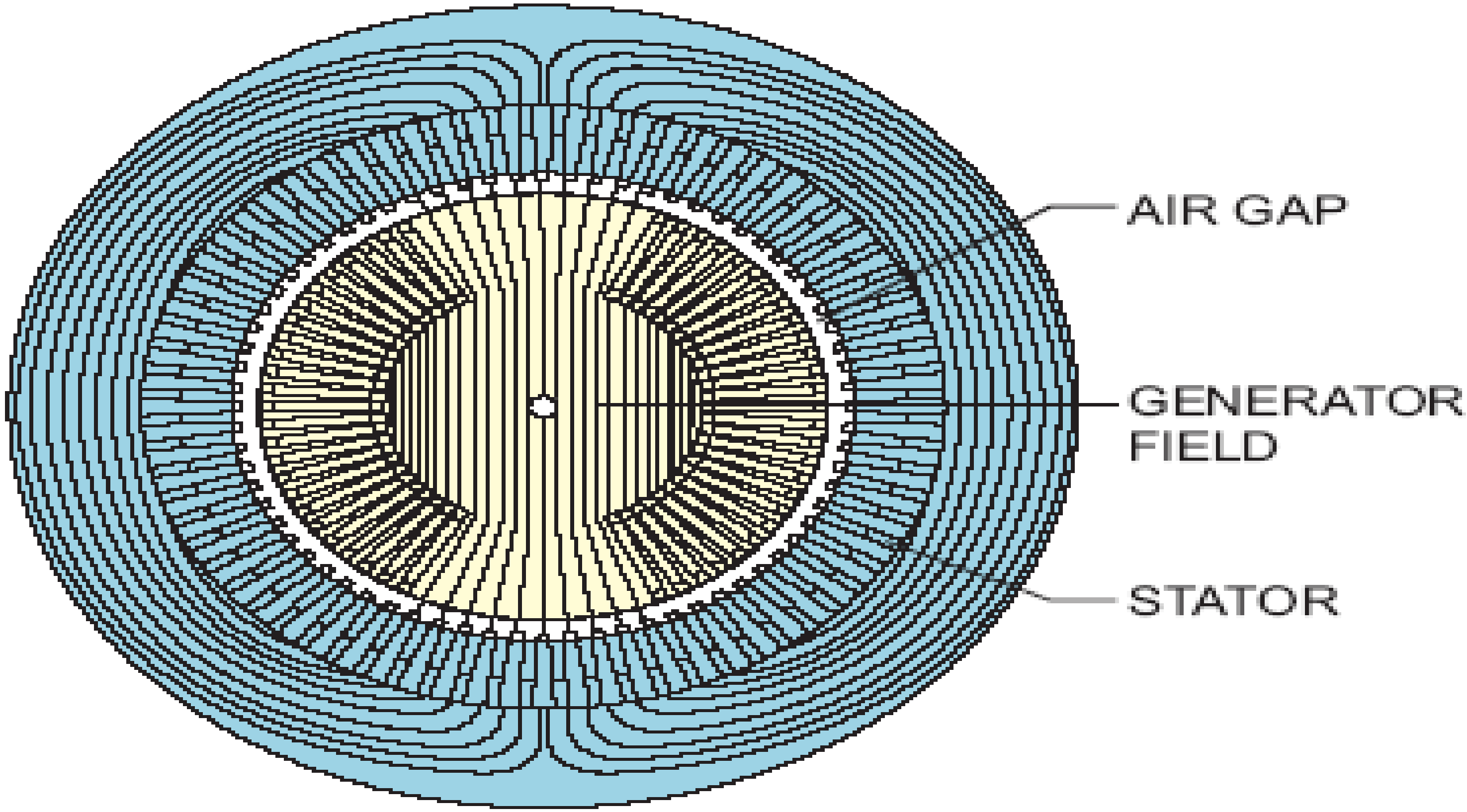
Stator

- Magnitude of voltage induced in the stator is a function of three factors:
  - Total lines of flux (field capability)
  - Frequency of the cutting the lines (operating speed)
  - Number of turns in the coils (stator capability)

Stator



Stator



Stator

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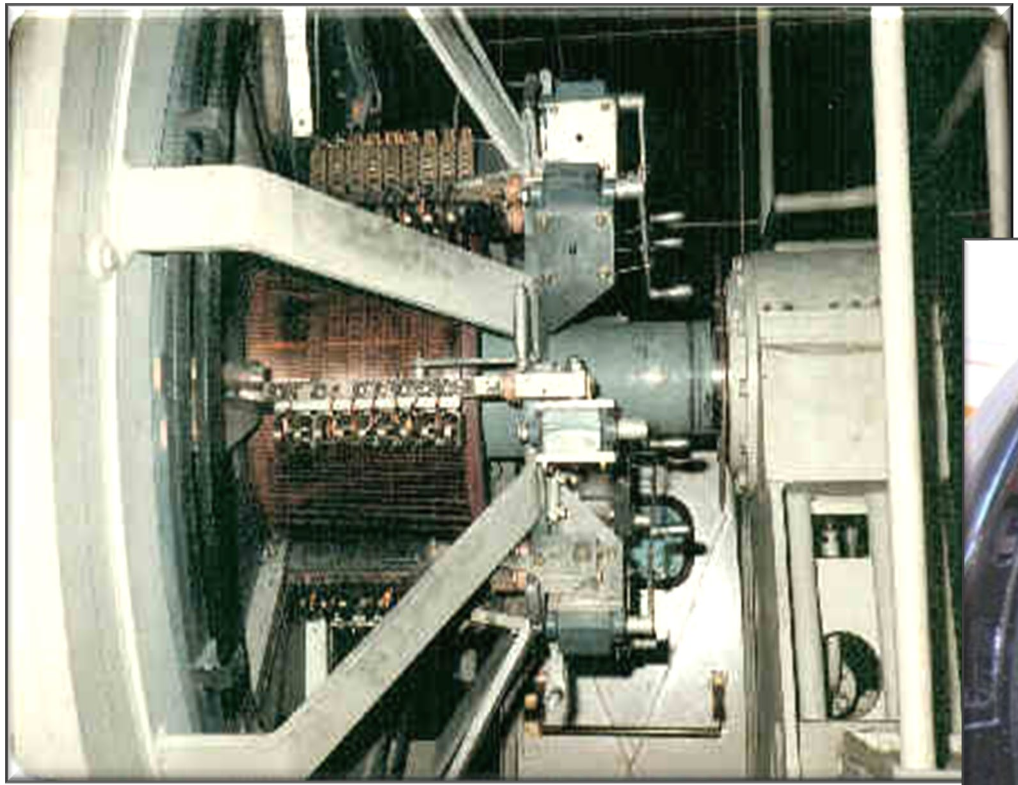
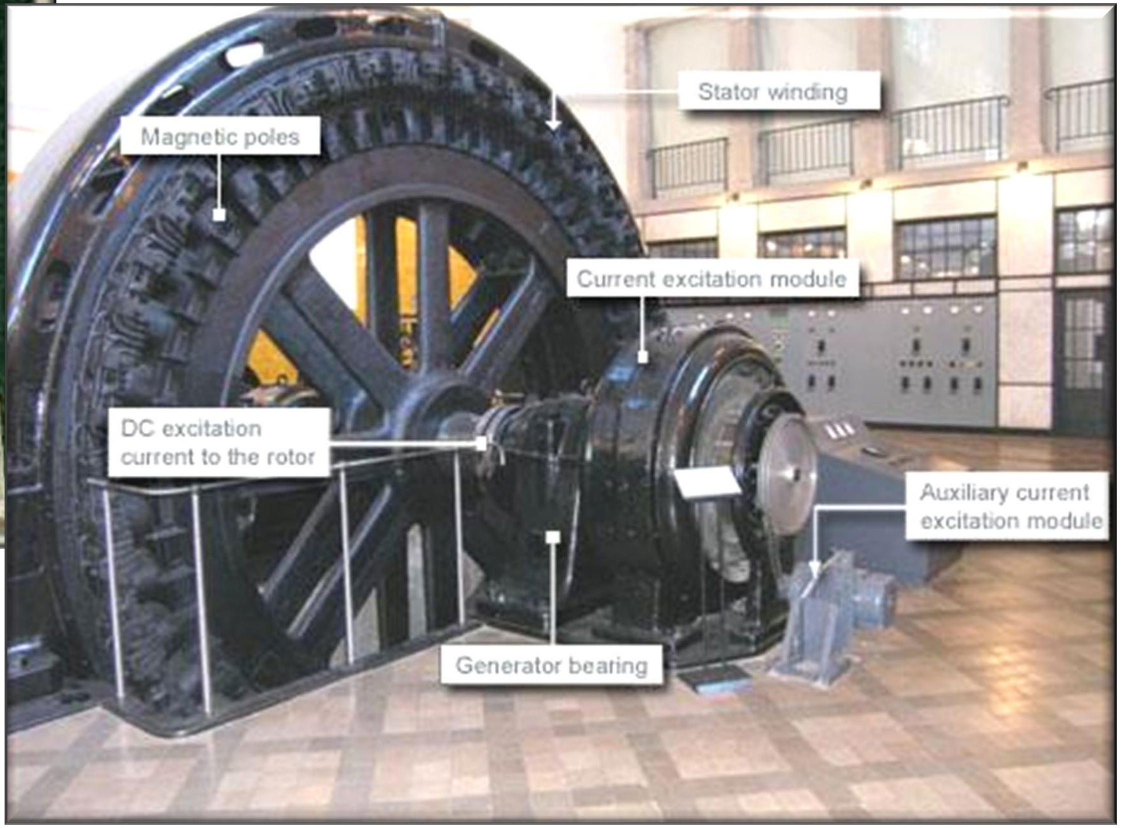
Stator

- Two-Pole Generators:
  - three armature winding coils installed in the stator
  - North and south poles of the rotor are 180˚ apart
- Four-Pole Generators:
  - six armature winding coils installed in the stator
  - North and south poles of the rotor are 90˚ apart
- A generator which is connected to the grid has a constant speed dictated by grid frequency

Bismark AC Generator Sim

Exciter





Stator winding
Magnetic poles
Current excitation module
DC excitation
current to the rotor
Auxiliary current
excitation module
Generator bearing

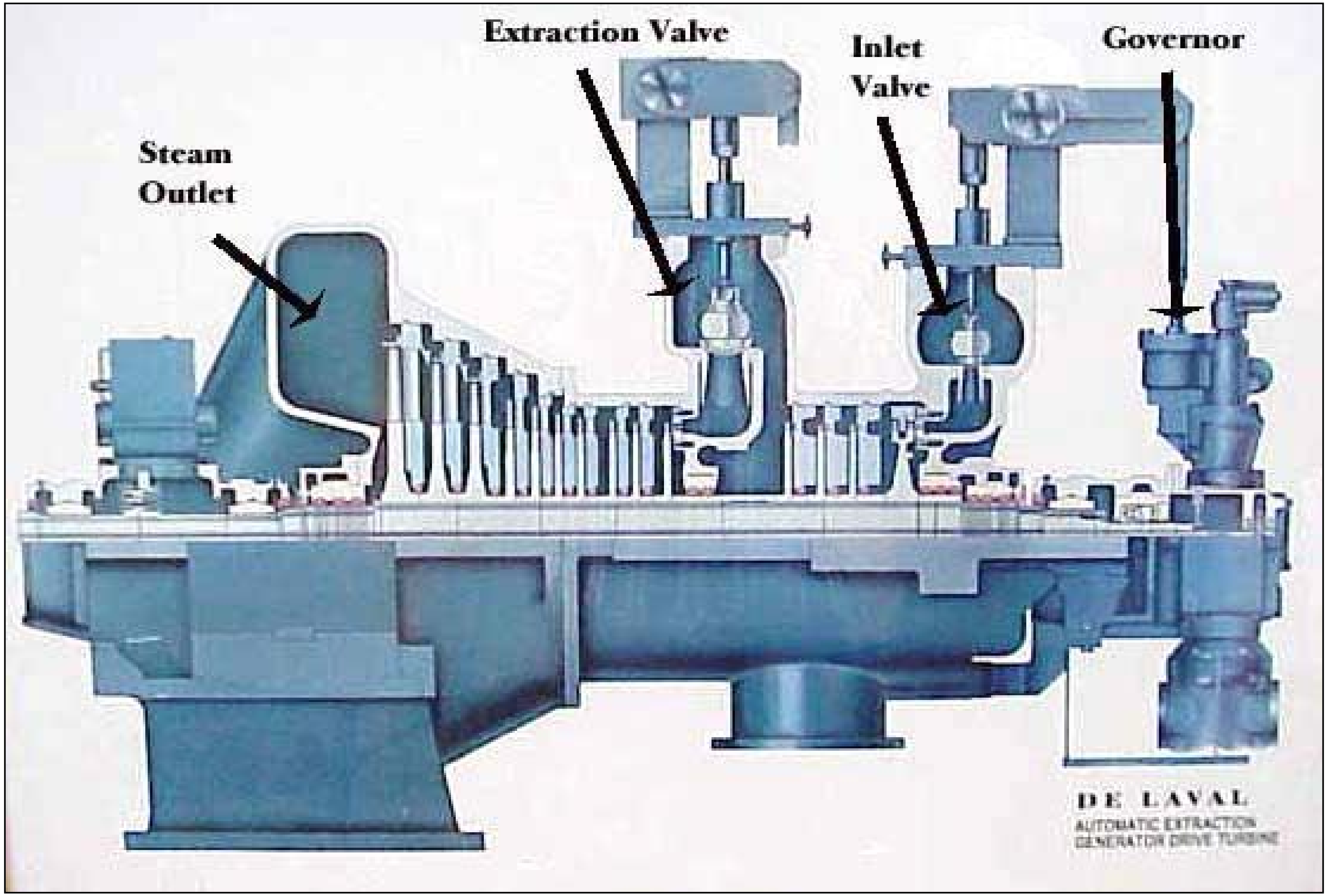
Exciter

- The excitation system provides direct current for the generator rotor/field windings through slip rings to produce the magnetic field
- Maintains generator voltage, controls MVAR flow, and assists in maintaining power system stability
- During load changes or disturbances on the system, the exciter must respond quickly to maintain the proper voltage at the generator terminals

Generator Governor Control

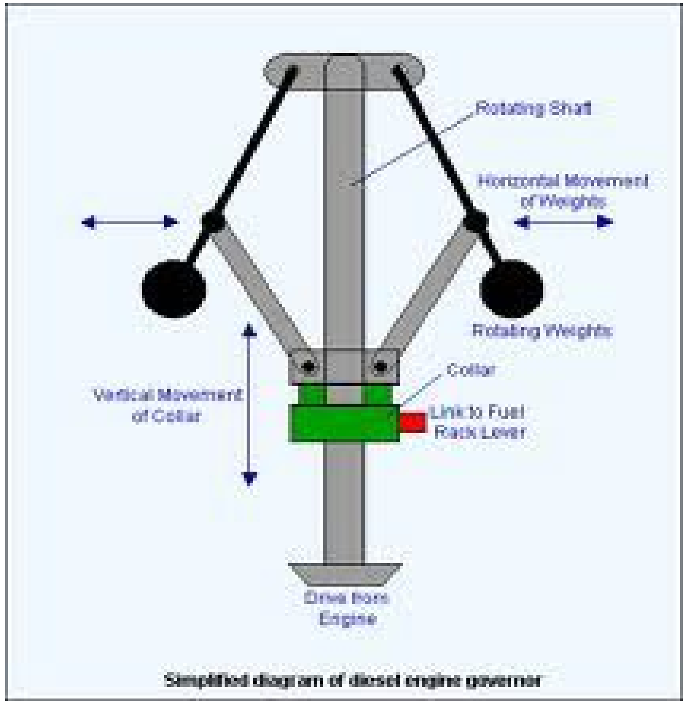
- Governors control generator shaft speed
- Adjust generation for small changes in load
- Operate by adjusting the input to the prime mover
  - Steam flow for fossil
  - Water flow for hydro
  - Fuel flow for combustion turbine
- Amount of governor control varies according to plant design
- Equivalent to a car's cruise control

Generator Governor Control

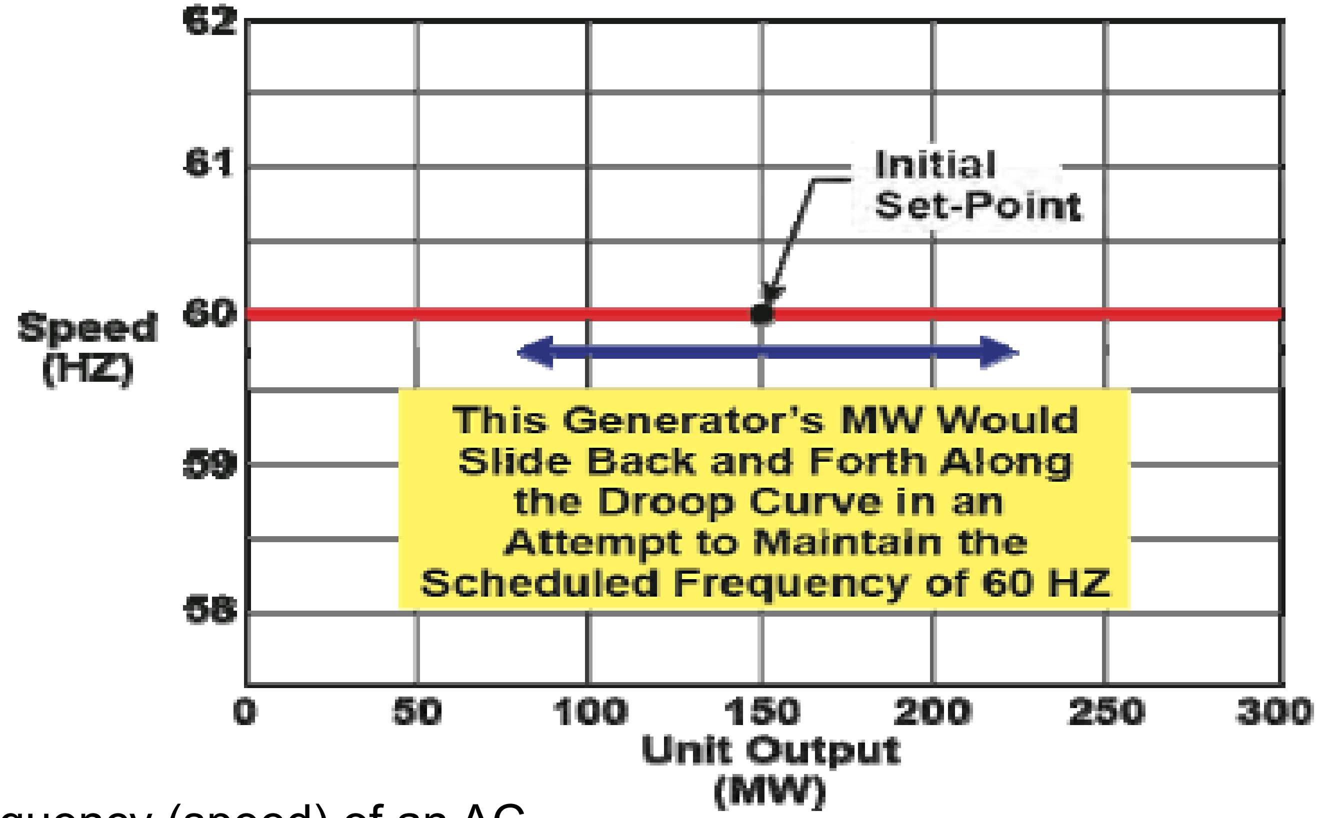


Generator Governor Control

- The Watt centrifugal governor was the mechanical means for governor control
  - Used weights that moved radially as rotational speed increased that pneumatically operated a servo-motor
  - Electrohydraulic governing has replaced the mechanical governor because of:
    - High response speed
    - Low deadband
    - Accuracy in speed and load control



Governor Control – Isochronous Mode



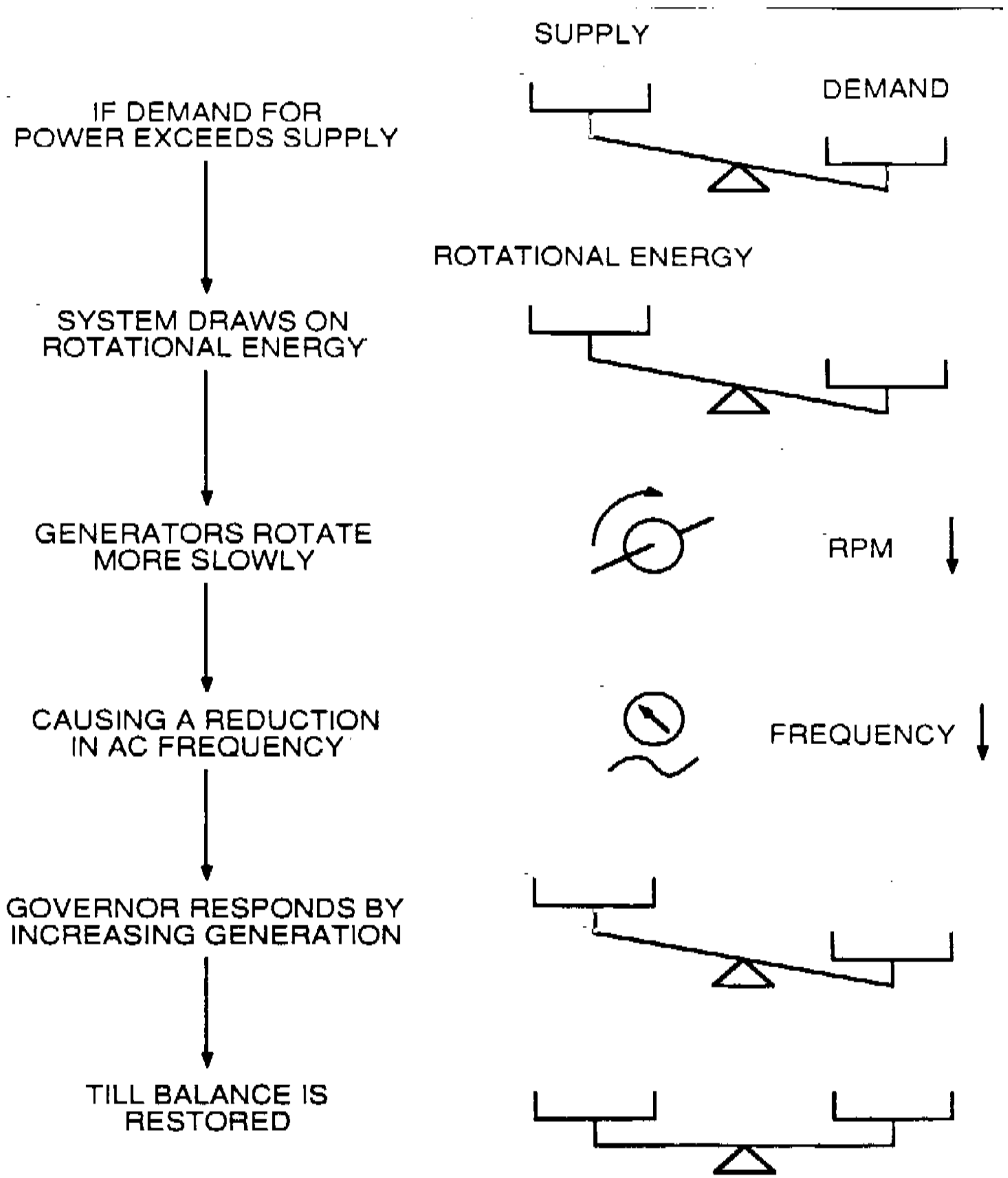
Controls the frequency (speed) of an AC generator

EPRI

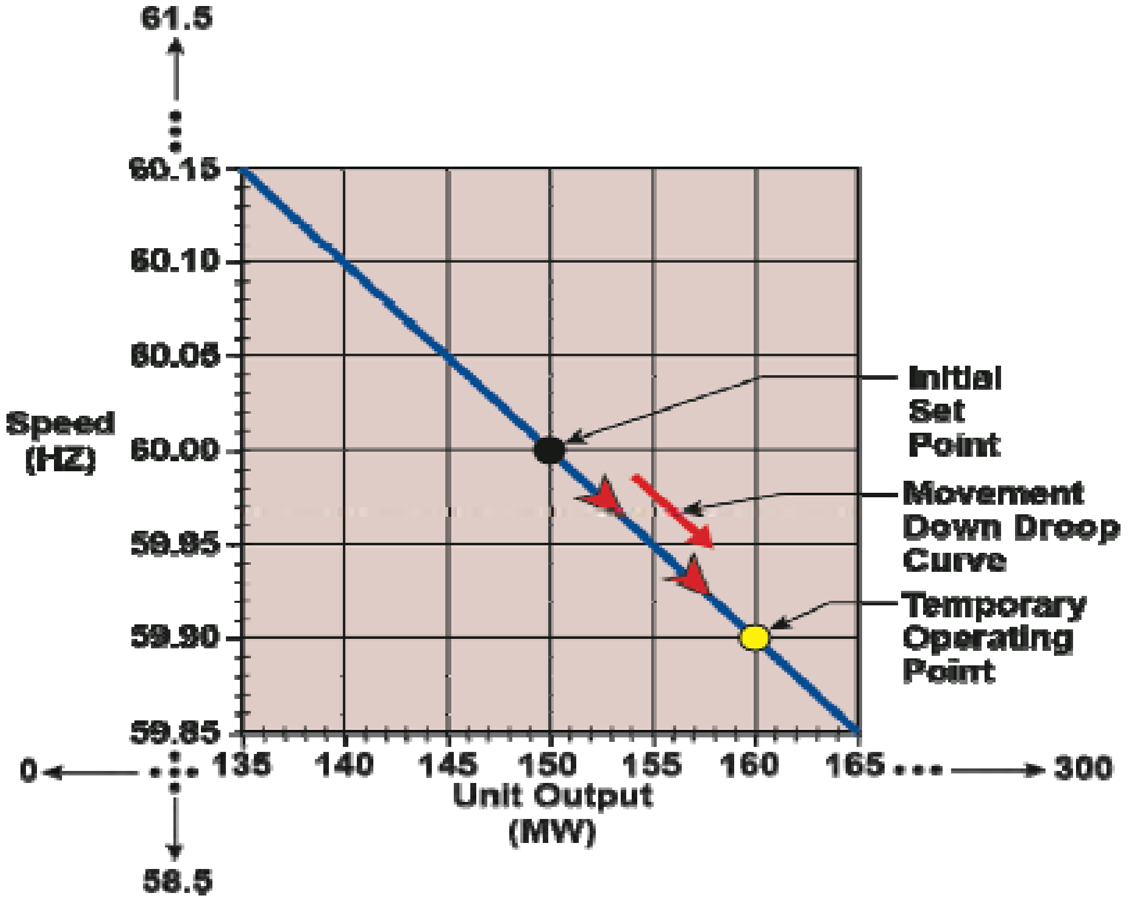
Governor Control

- When a generator synchronizes to the system
  - It couples itself to hundreds of other machines rotating at the same electrical speed
  - Each of these generators have a “droop” feature added to their governor
  - This allows generators to respond in proportion to their size whenever there is a disturbance, or load-resource mismatch

Governor Control

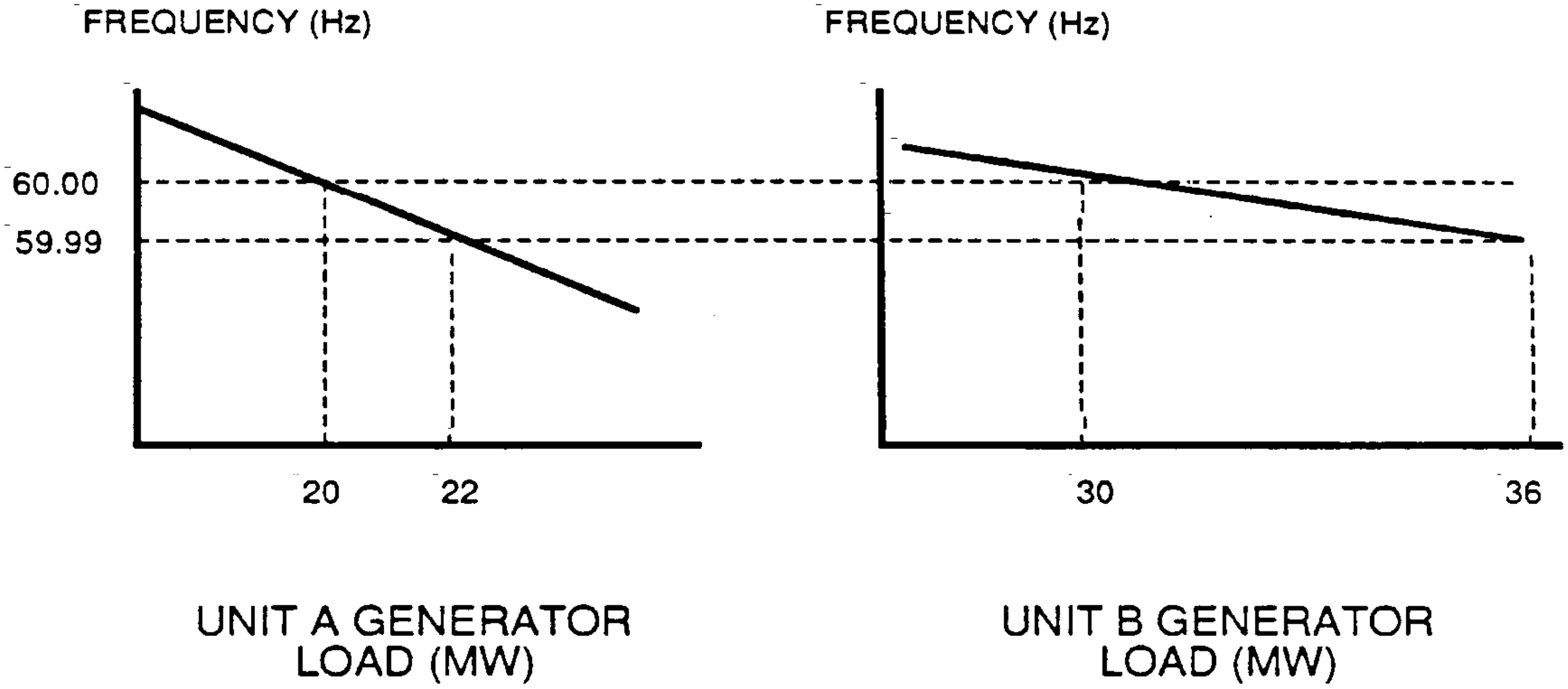


Governor Control – Droop Speed Mode



EPRI

Generator Governor Control: Droop



LOAD PICK-UP FOR A:

2MW FOR 0.01 Hz

LOAD PICK-UP FOR B:

6MW FOR 0.01 Hz

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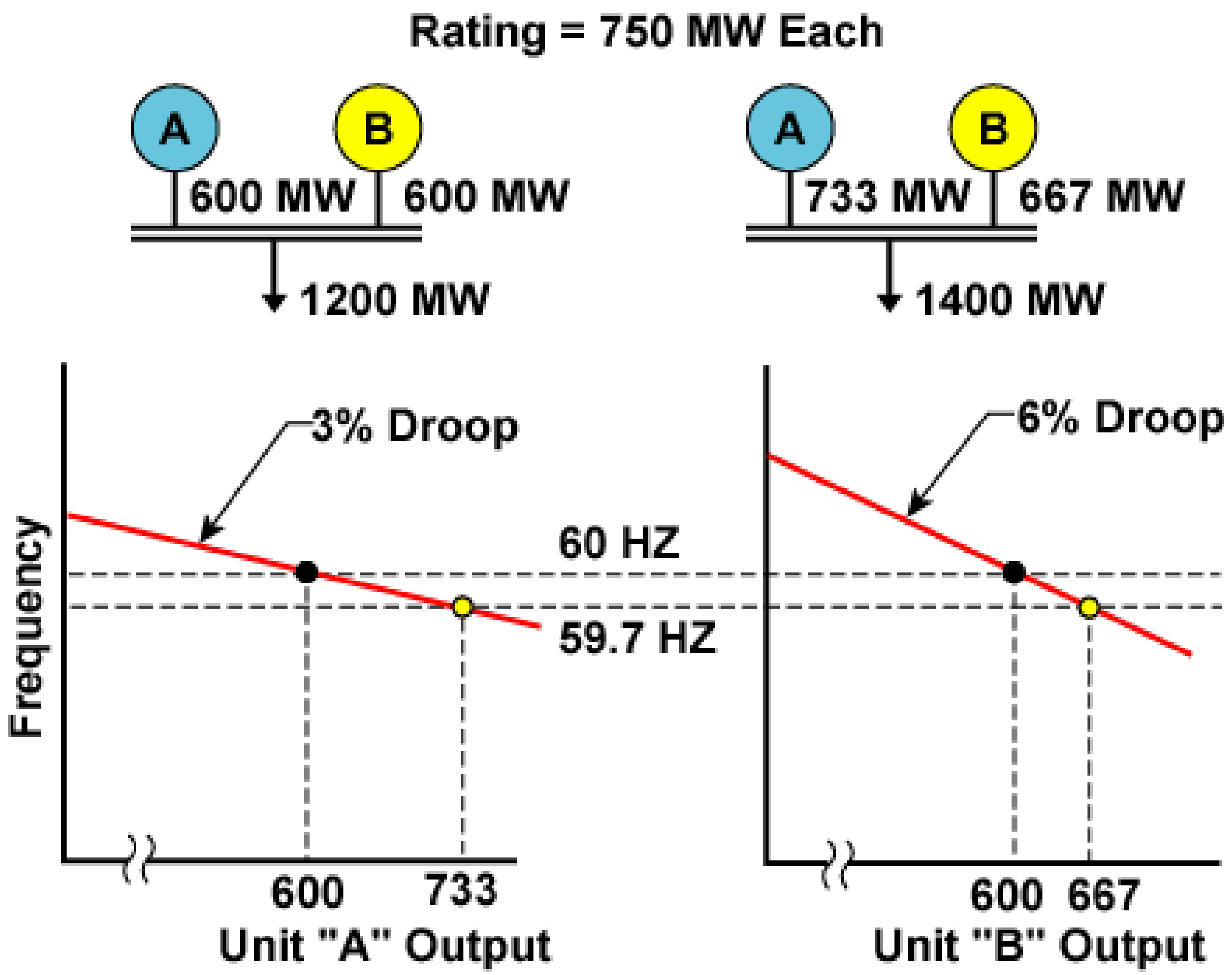
Governor Control



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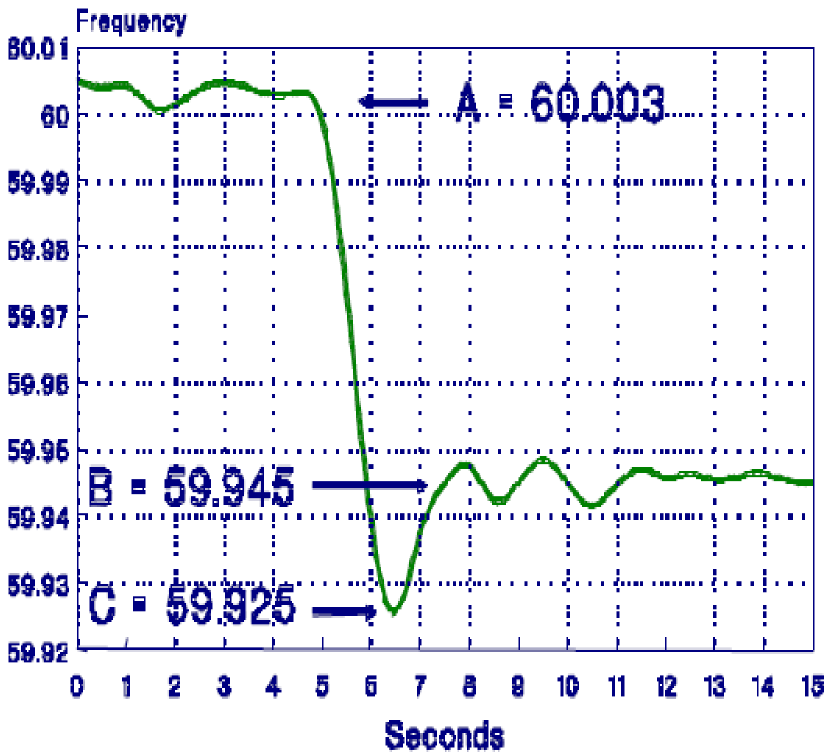
Generator Governor Control

Frequency Response



- Load
  - Rate of frequency decline from points A to C is slowed by "load rejection" and inertia
- Generators
  - Generator governor action halts the decline in frequency and causes the "knee" of the excursion, and brings the frequency back to point B from point C

It is important to note that frequency will not recover from point B to 60 Hz until the deficient control area replaces the amount of lost generation

Generator Governor Control: Droop

- A droop characteristic forces generators to respond to frequency disturbances in proportion to their size
- Droop settings enable many generators to operate in parallel while all are on governor control and not compete with one another for load changes

Governor Control

- Deadband
  - An additional feature displayed by generators
  - The amount of frequency change a governor must “see” before it starts to respond
  - Natural feature of the earliest governors caused by gear lash (looseness or slop in the gear mechanism)
  - Serves a useful purpose by preventing governors from continuously “hunting” as frequency varies ever so slightly

Generator Rotational Speed

- A generator which is connected to the grid has a constant speed which is dictated by grid frequency
- Doubling the magnets or windings in the stator ensures that the magnetic field rotates at half speed
- When doubling the poles in the stator, the magnets in the rotor must also be doubled

Generator Rotational Speed

- Frequency is dependent on:
  - Number of field poles
  - Speed of the generator
- f = (N)(P)/120, where

f = frequency (Hz)

N = rotor speed (rpm)

P = total number of poles

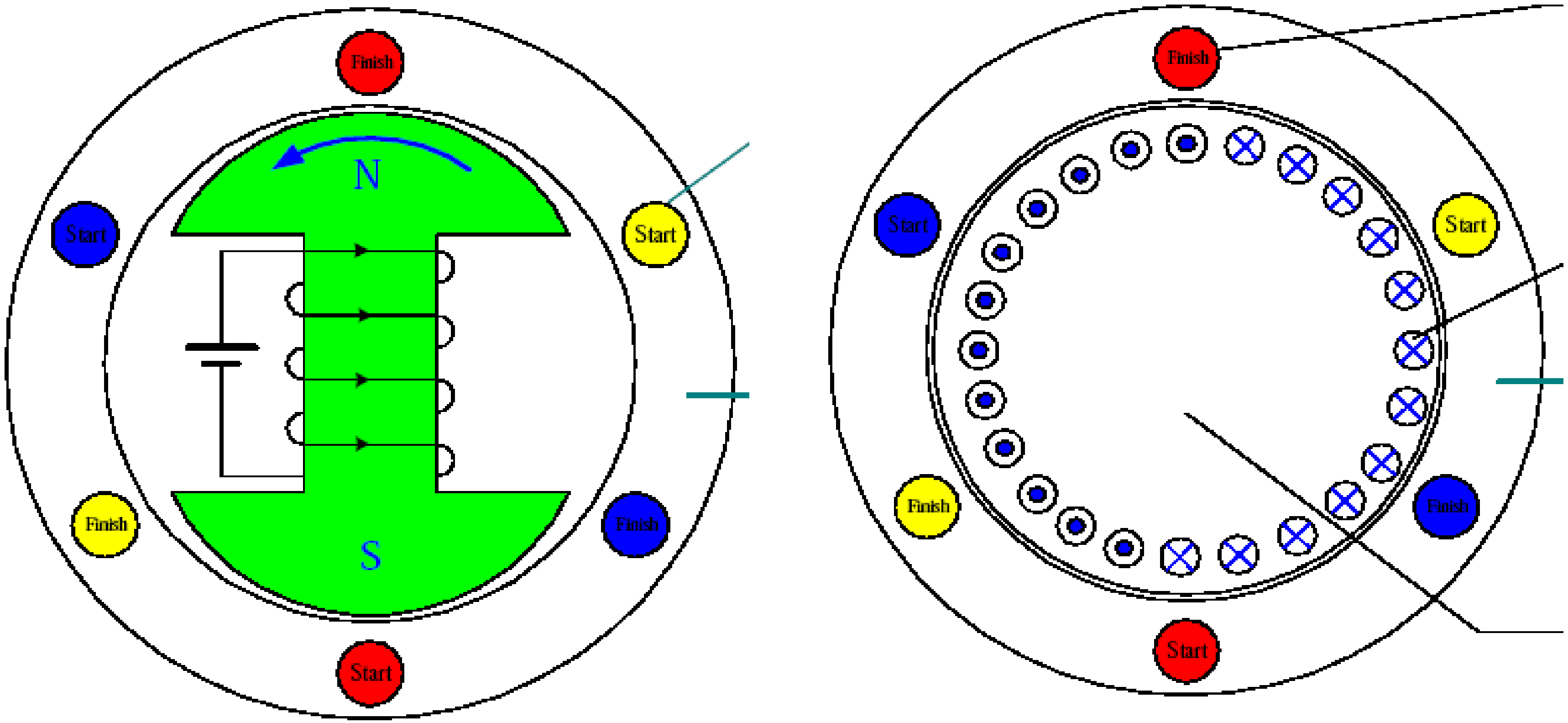
120 = Conversion from minutes to seconds and from “poles” to “pole pairs”

(60 seconds/1 minute) x (2 poles/pole pair)

Generator Rotational Speed

Example: 2 Poles

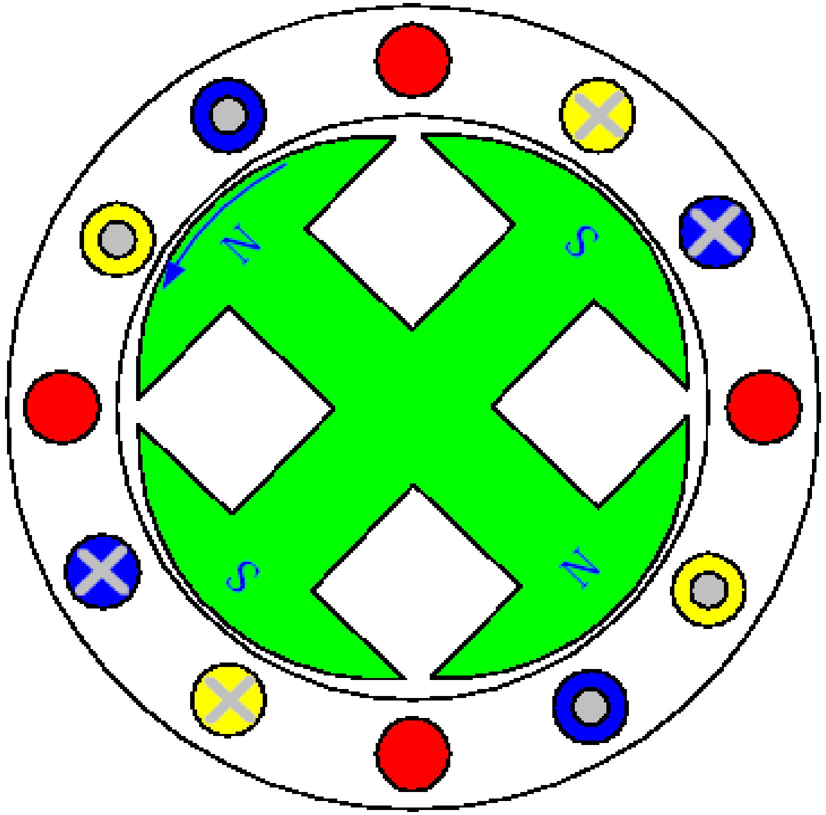
60 Hz = (3600 RPM)(2 Poles)/120

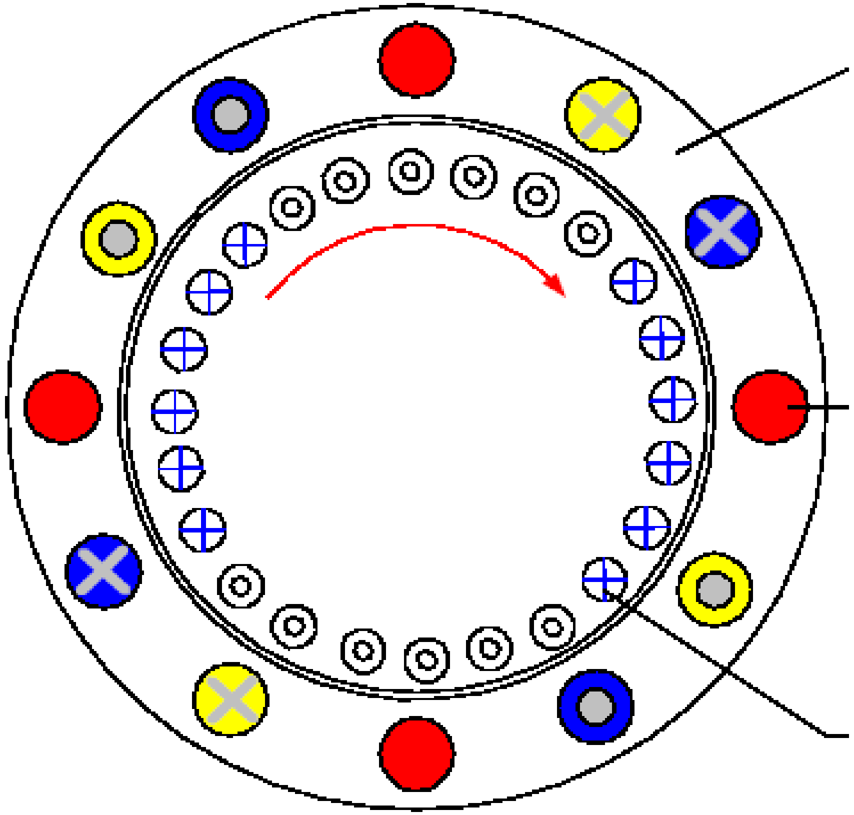


Generator Rotational Speed

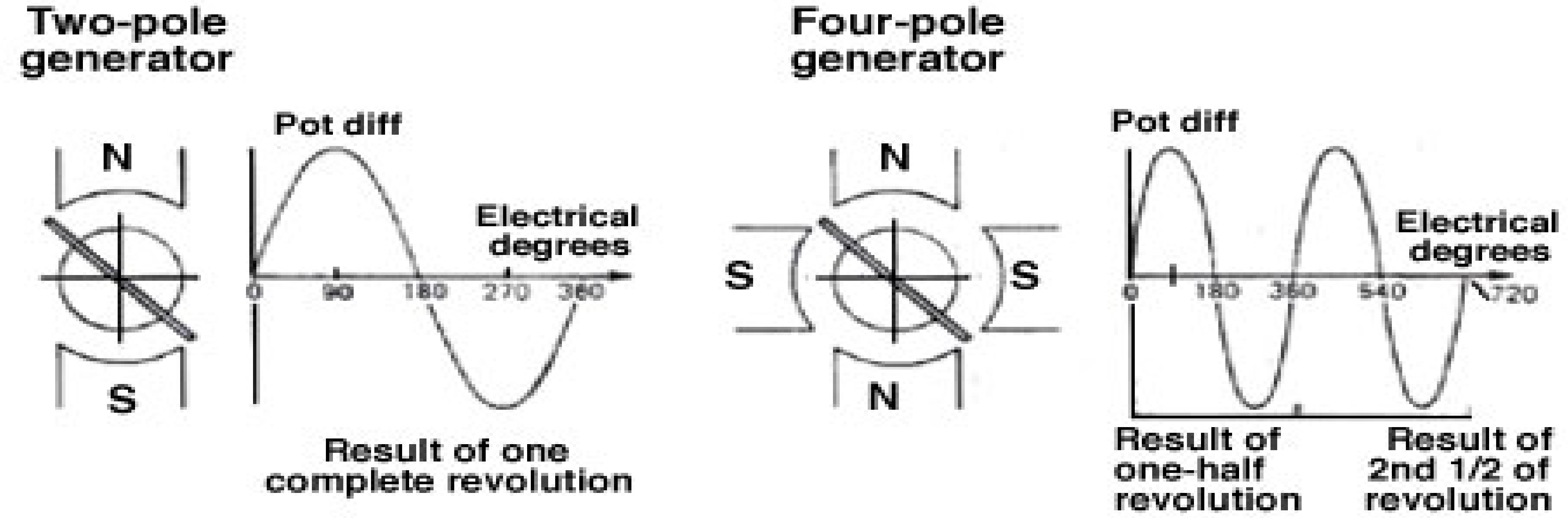
Example: 4 Poles

60 Hz = (1800 RPM)(4 Poles)/120



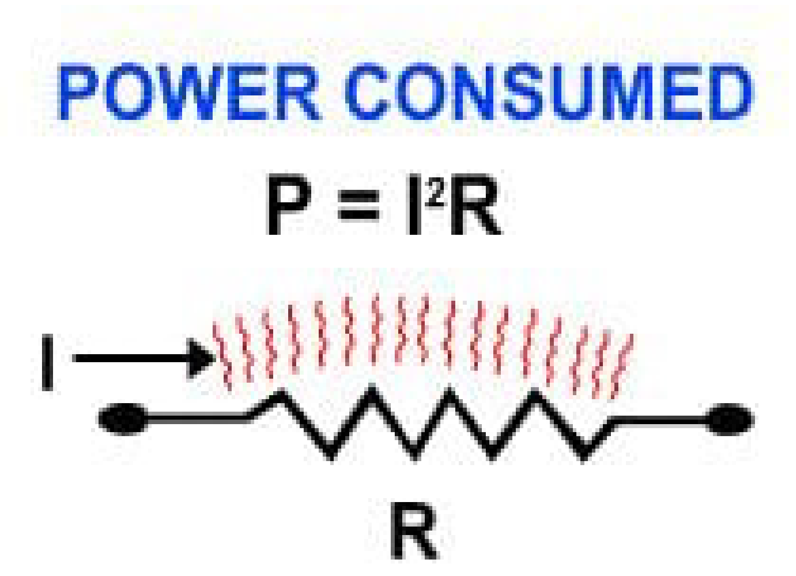


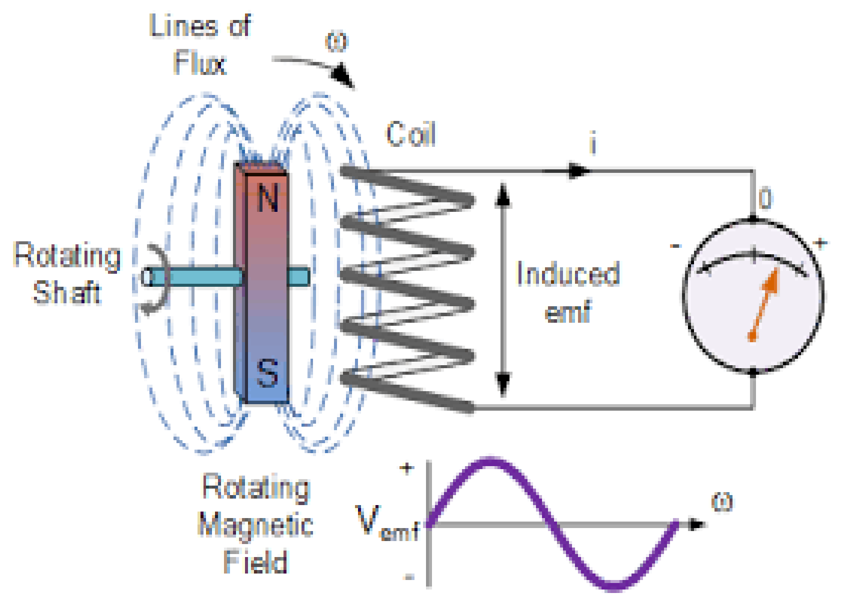
Generator Rotational Speed



Generator Characteristics

- Generator limitation factors
  - Power capability of the prime mover
  - Heating of generator components (I^2R losses)
  - Magnetic field strength to transfer power from the rotor to the generator output

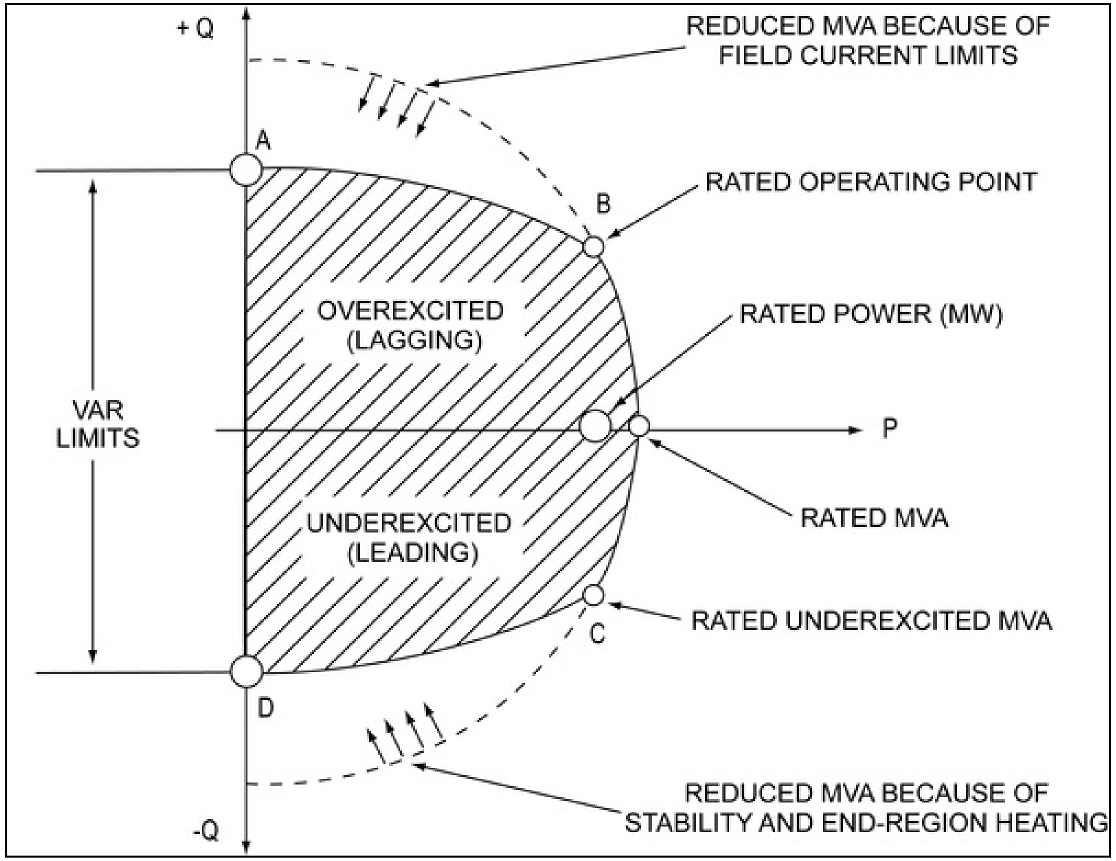




Reactive Capability Limitations

Generating Unit

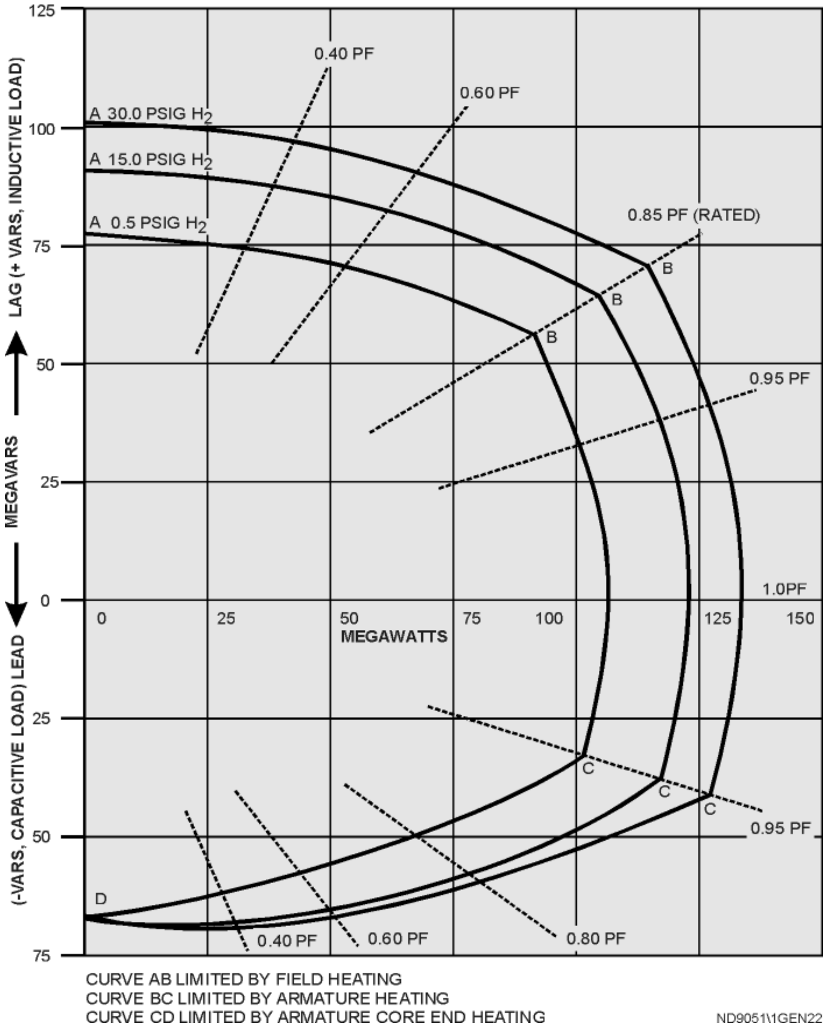
- MVAR output limited by D-curve
- Voltage regulator limits
- Power factor limits
- MW tradeoff



Restrictions and Limitations

- Affects on the surrounding Power System:
  - Must coordinate shifts in generation to obtain desired MVAR flows and voltage adjustments
  - Should coordinate generation voltage adjustments with switchable sources (capacitors and reactors)
  - Do not remove all VAR reserve from a generating unit

Capability Curve/Limitations



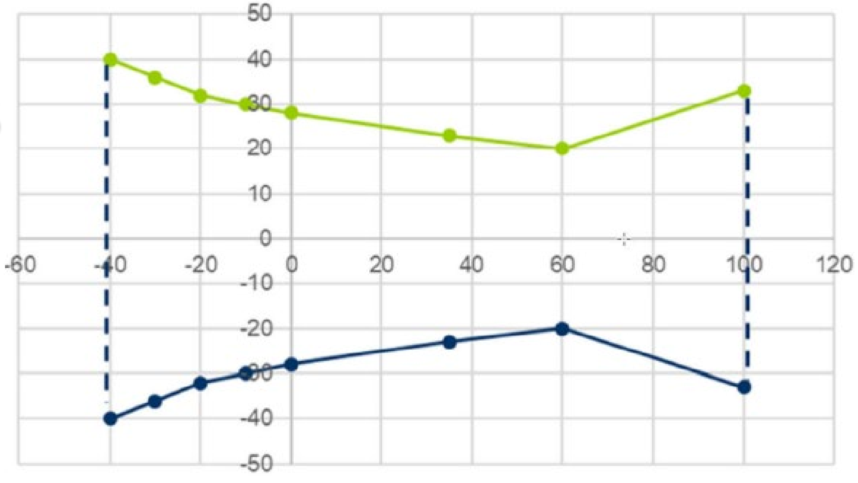


Exhibit 15: Example of inverter-based AC-coupled open-loop Hybrid Resource with 100 MW solar and 40 MW b

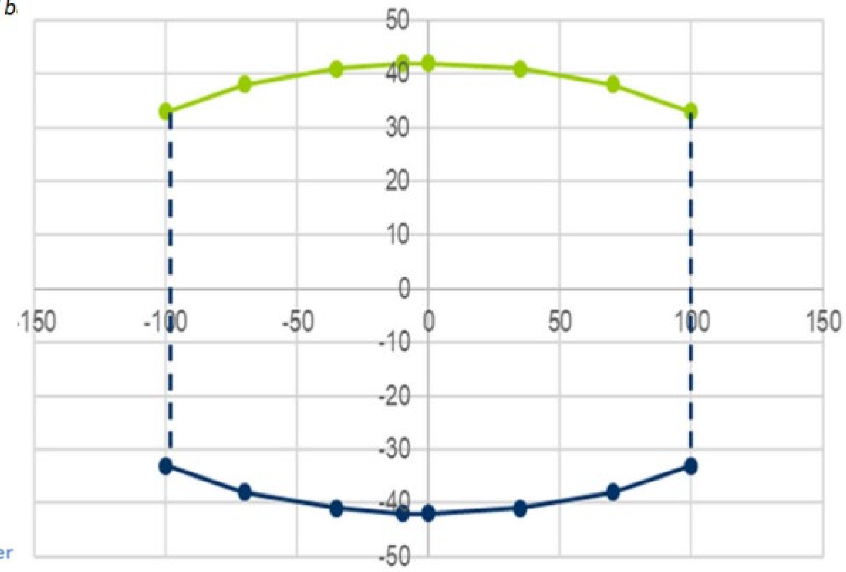
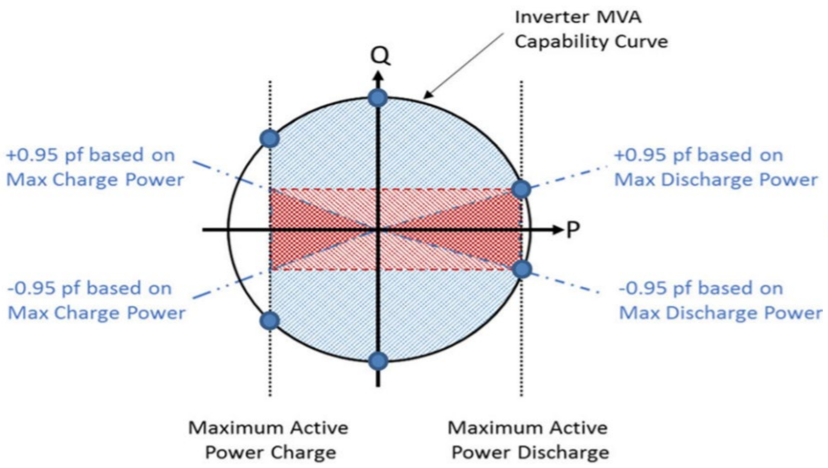
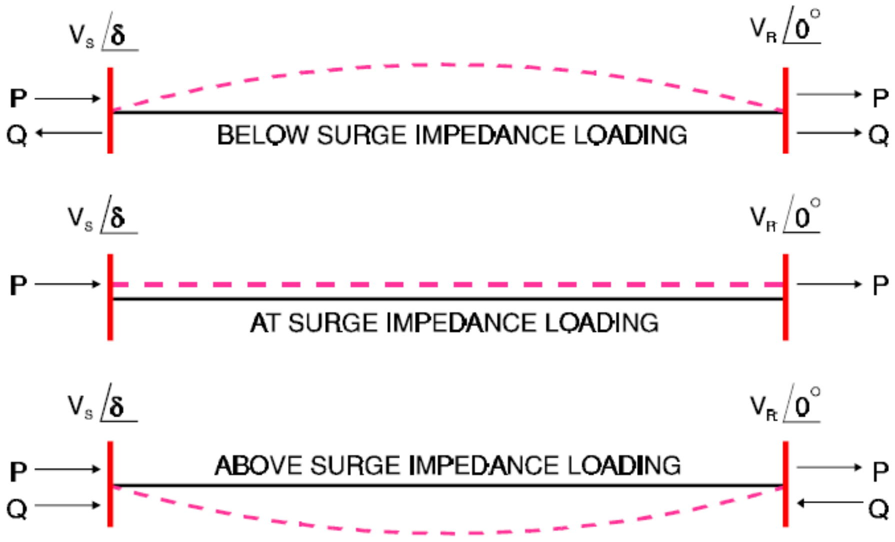


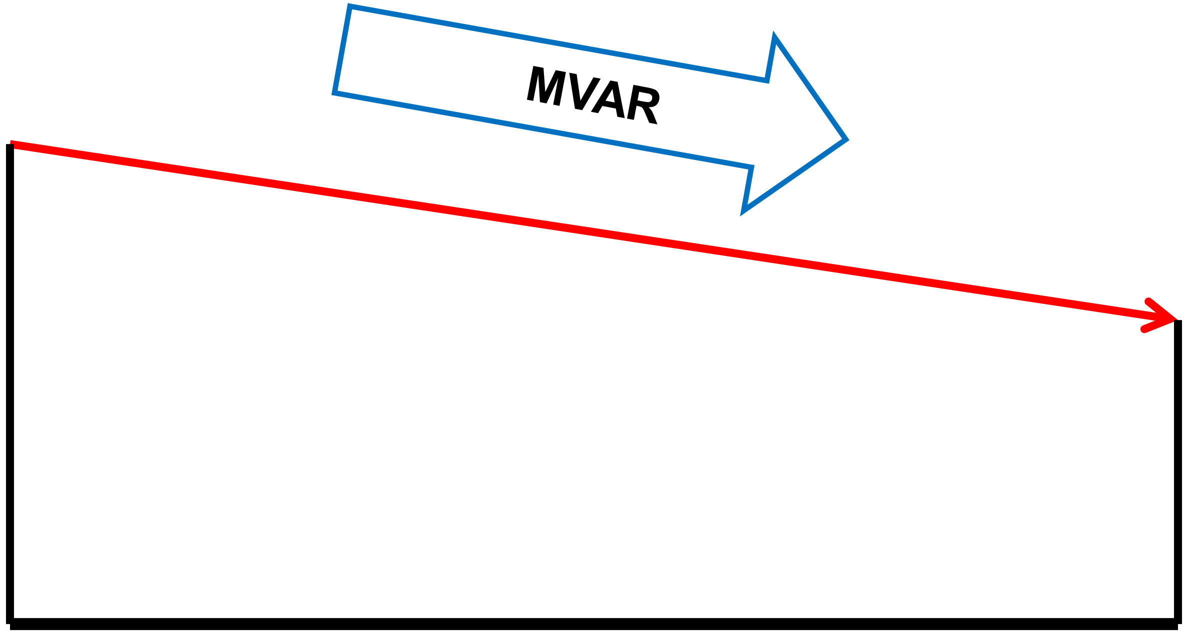
Exhibit 16: Example of inverter-based DC-coupled open-loop solar-storage Hybrid Resource with 100 MW solar and 100 MW battery.



MVAR Flow & Voltage

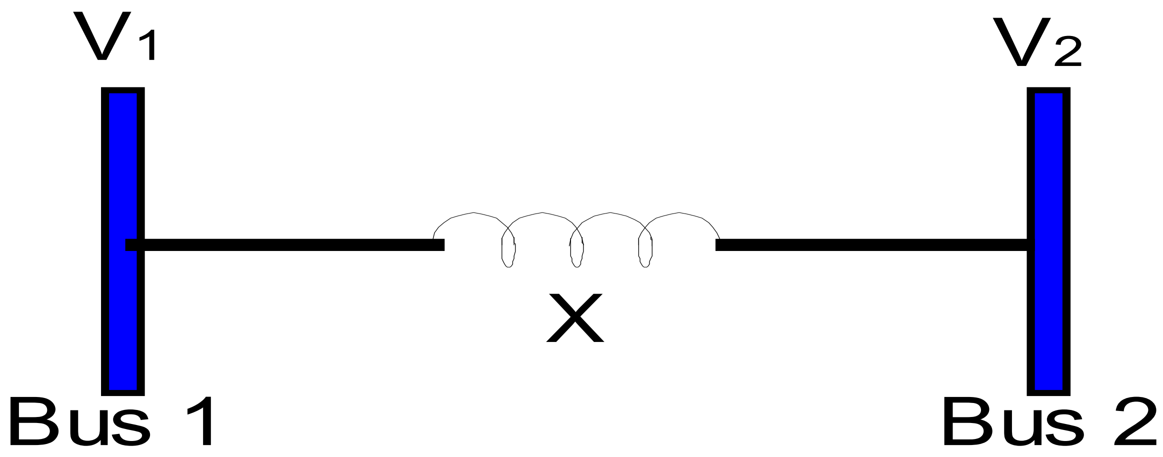
- MVARs flow "downhill" based on voltage
- Flow from high per unit voltage to low per unit voltage





MVAR Flow & Voltage

- MVAR flow between buses is determined by magnitude difference between bus voltages
- Voltage magnitude difference is driving for MVAR flow
- The greater the voltage drop or rise between 2 locations – the greater the MVAR flow

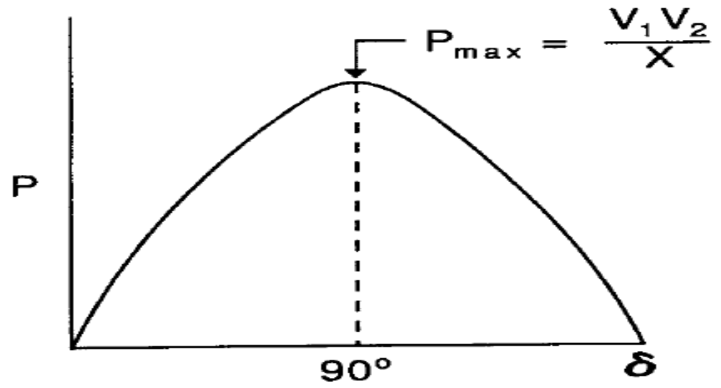


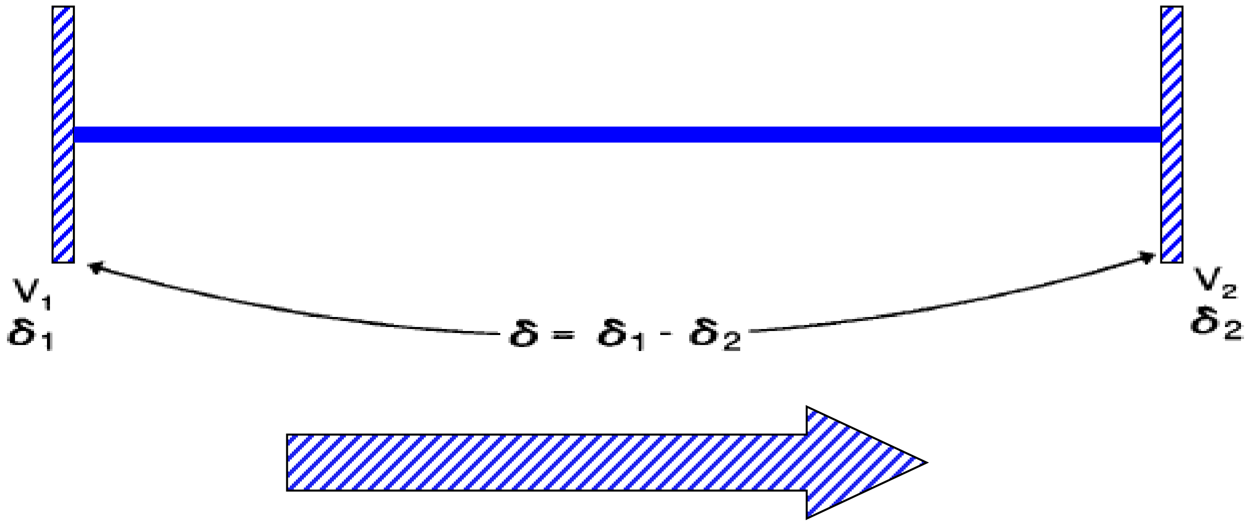
$$\text{VARs} = \frac{V_1 (V_1 - V_2)}{X}$$

MW Flow & Power Angle

- MW flow between buses is determined by phase angle difference between voltages at the buses
- Phase angle difference between voltages is called Power Angle which is represented by the symbol Delta δ

$$P = \frac{V_1 V_2}{X} \text{SIN}(\delta)$$



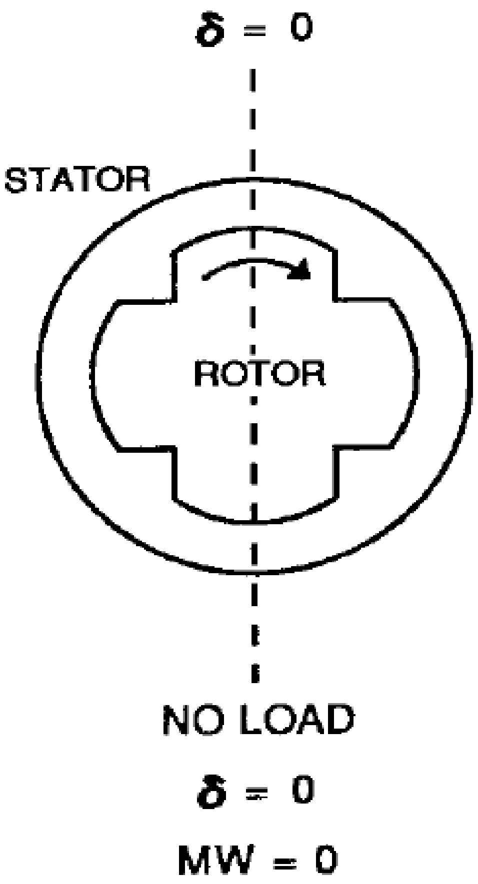


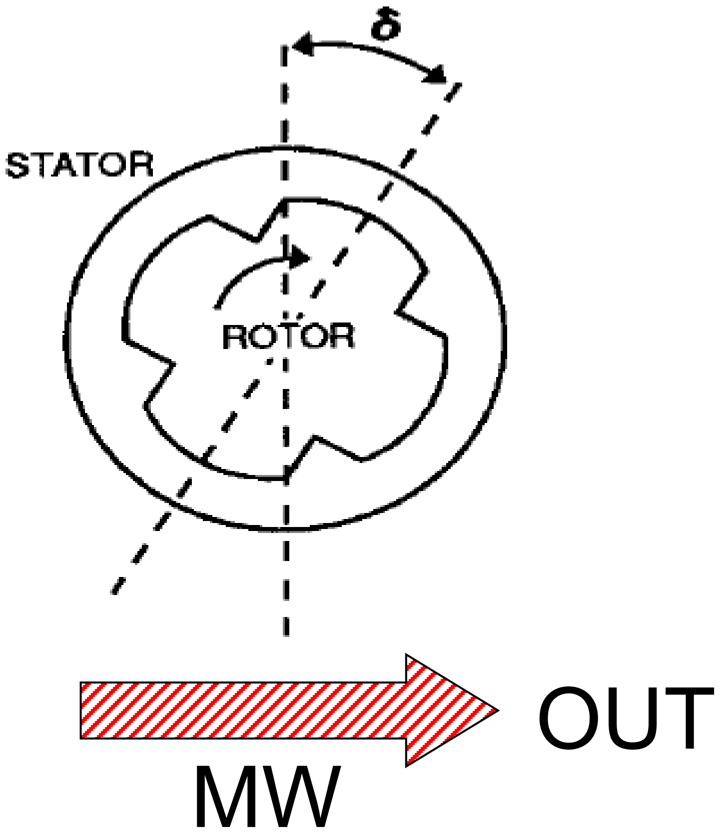
Generator MW Flow & Power Angle

- Rotor Angle
  - On a transmission system is similar to rotor angle
    - Load or Torque angle
  - No Load
    - Field pole of rotor is "in phase" with stator armature windings
    - $\delta = 0$
  - Load Added
    - Rotor advances with respect to the stator
    - MW's flow out of the machine

Bismark Torque Angle Sim

MW Flow & Power Angle





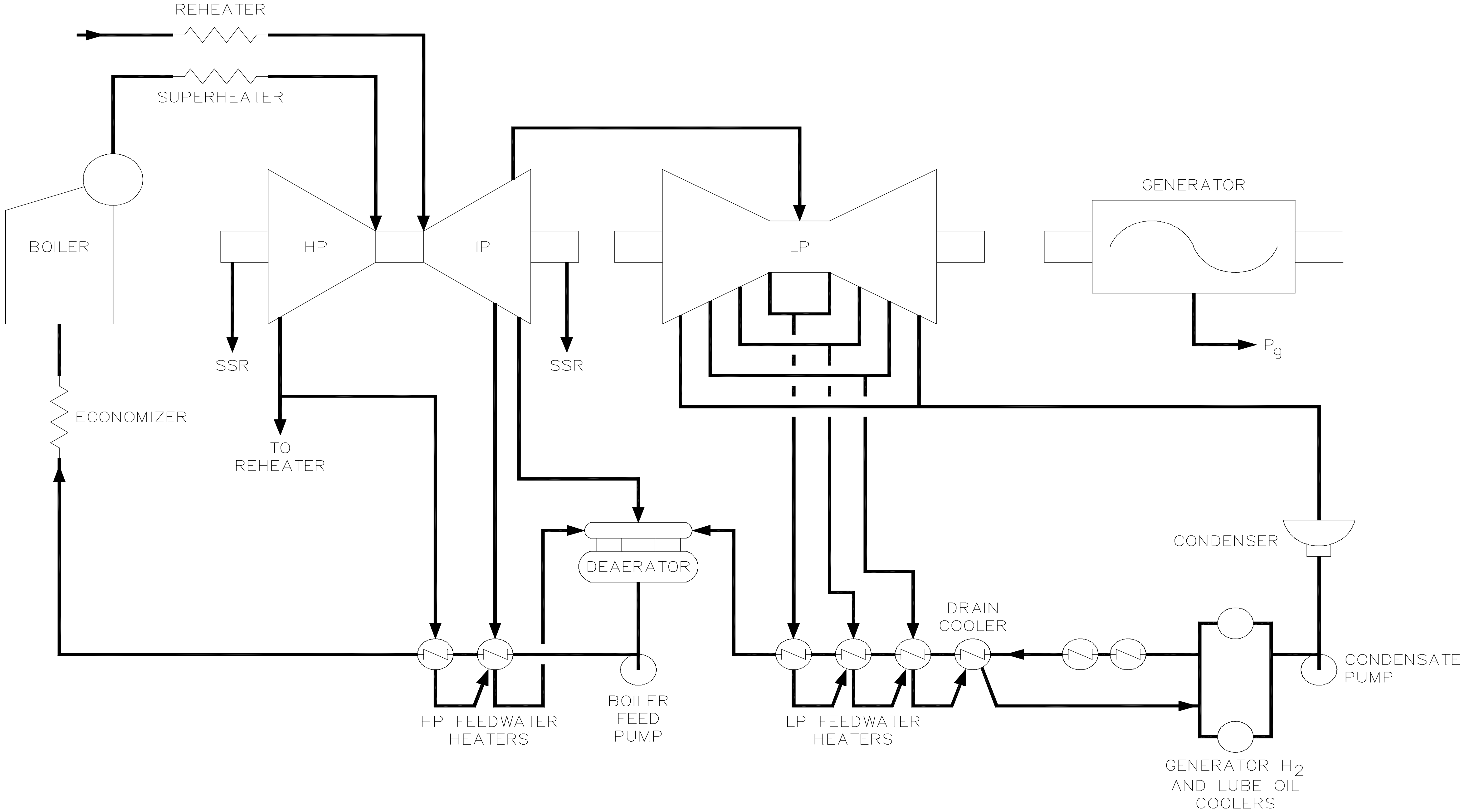
Basic Steam Cycle

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

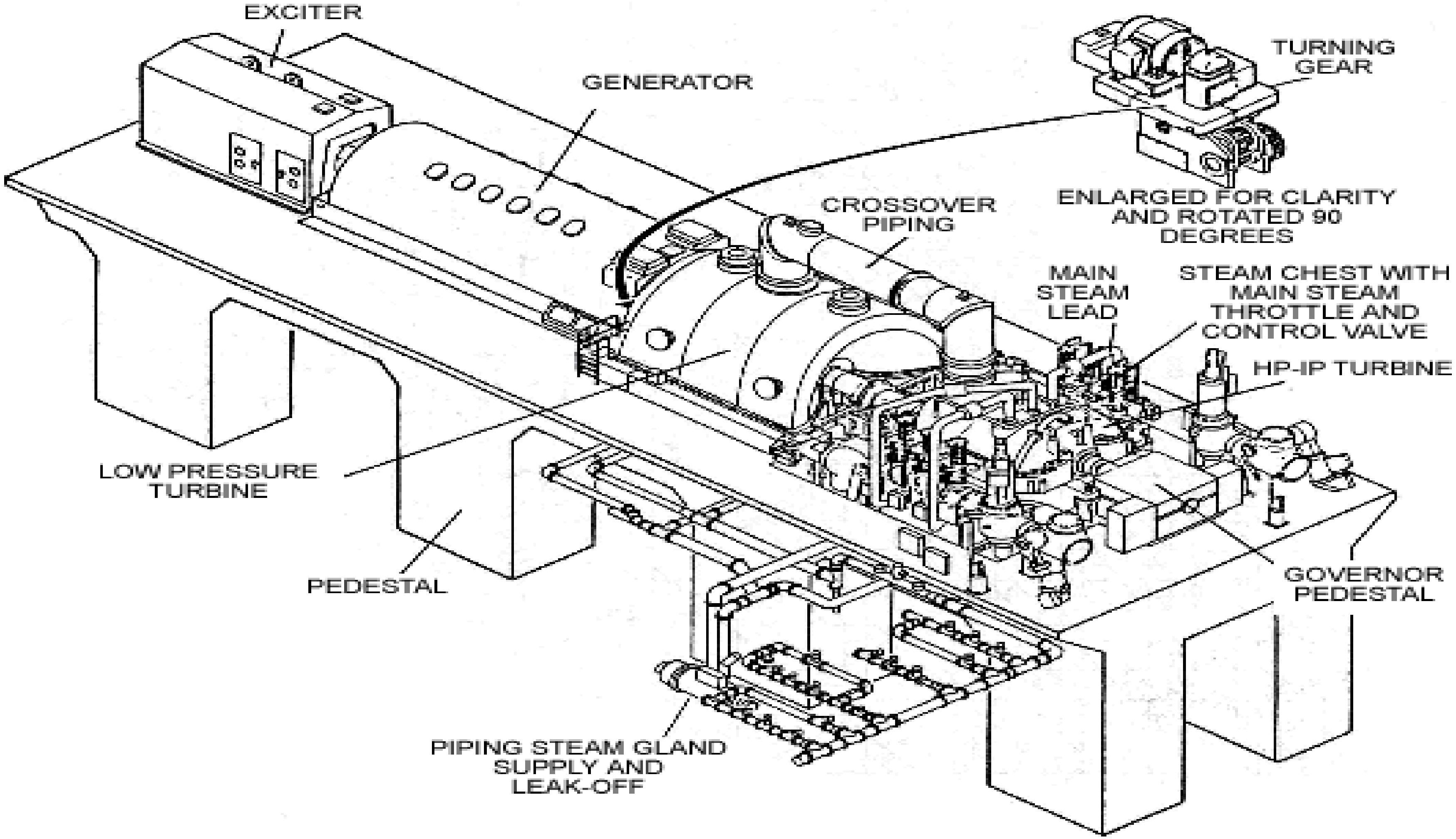
Simple Steam Cycle

- Four Phases - Steam/Water Cycle *(con't.)*
  - **Condensation** (Condensate System)
    - Remaining low energy steam is condensed 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
P_g
SSR
SSR
ECONOMIZER
TO REHEATER
DEAERATOR
CONDENSER
DRAIN COOLER
HP FEEDWATER HEATERS
BOILER FEED PUMP
LP FEEDWATER HEATERS
CONDENSATE PUMP
GENERATOR H_2 AND LUBE OIL COOLERS

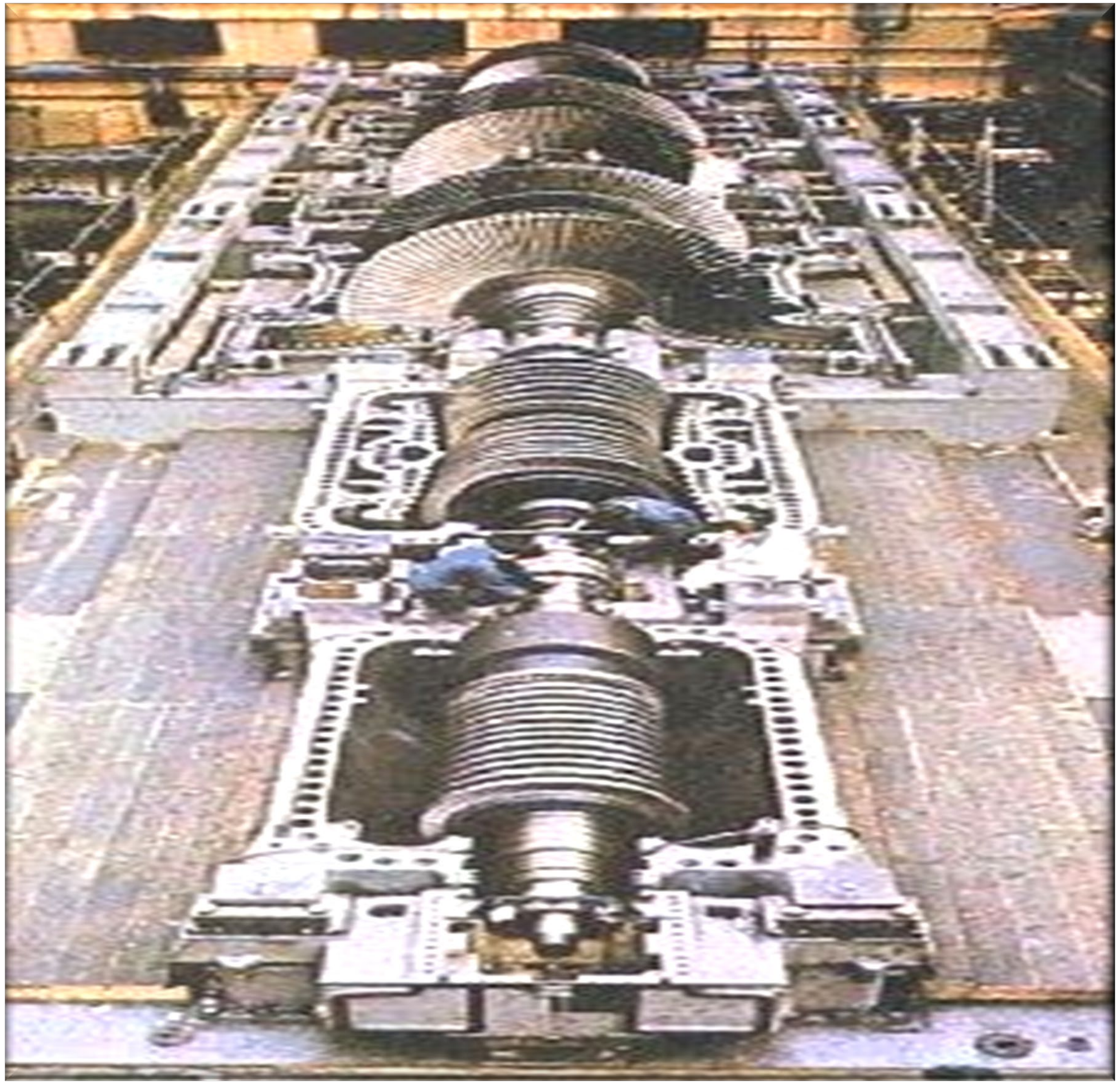
6244

The Steam Turbine



A TYPICAL POWER STATION STEAM TURBINE AND ITS EXTERNAL EQUIPMENT

The Steam Turbine



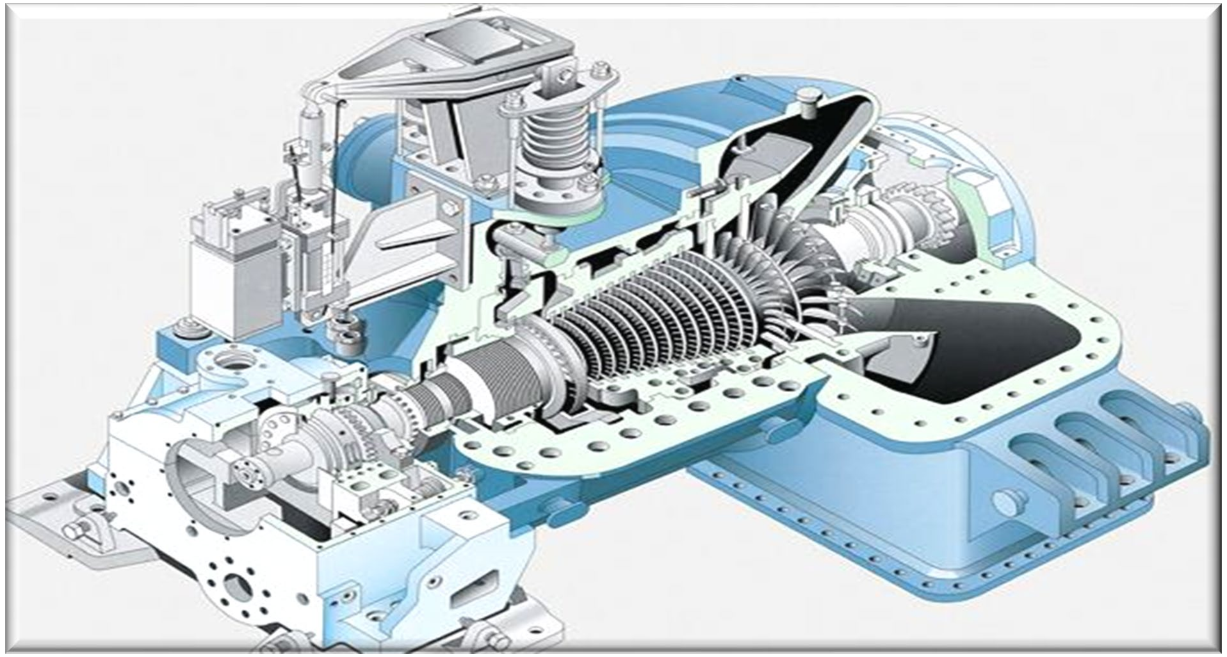
The Steam Turbine

- 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

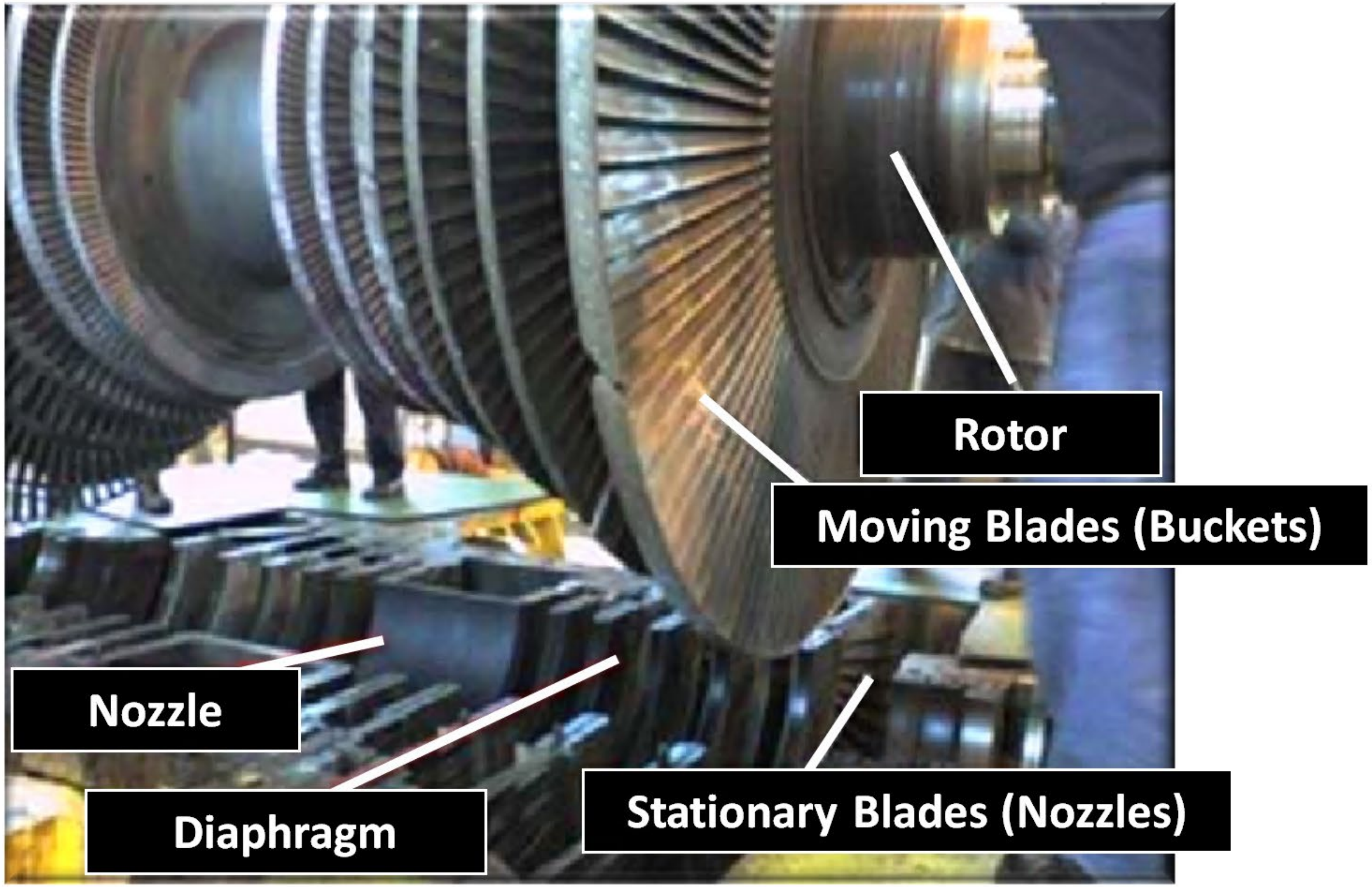
http://www.youtube.com/watch?v=qvIi3JDkADI

The Steam Turbine

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



Steam Turbine - Blading



The Steam Turbine

- Auxiliary Turbine Equipment
  - **Bearings** - 2 types:
    - Thrust - axially locate the turbine shaft in its correct position
    - 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 unbalanced conditions before damage can occur

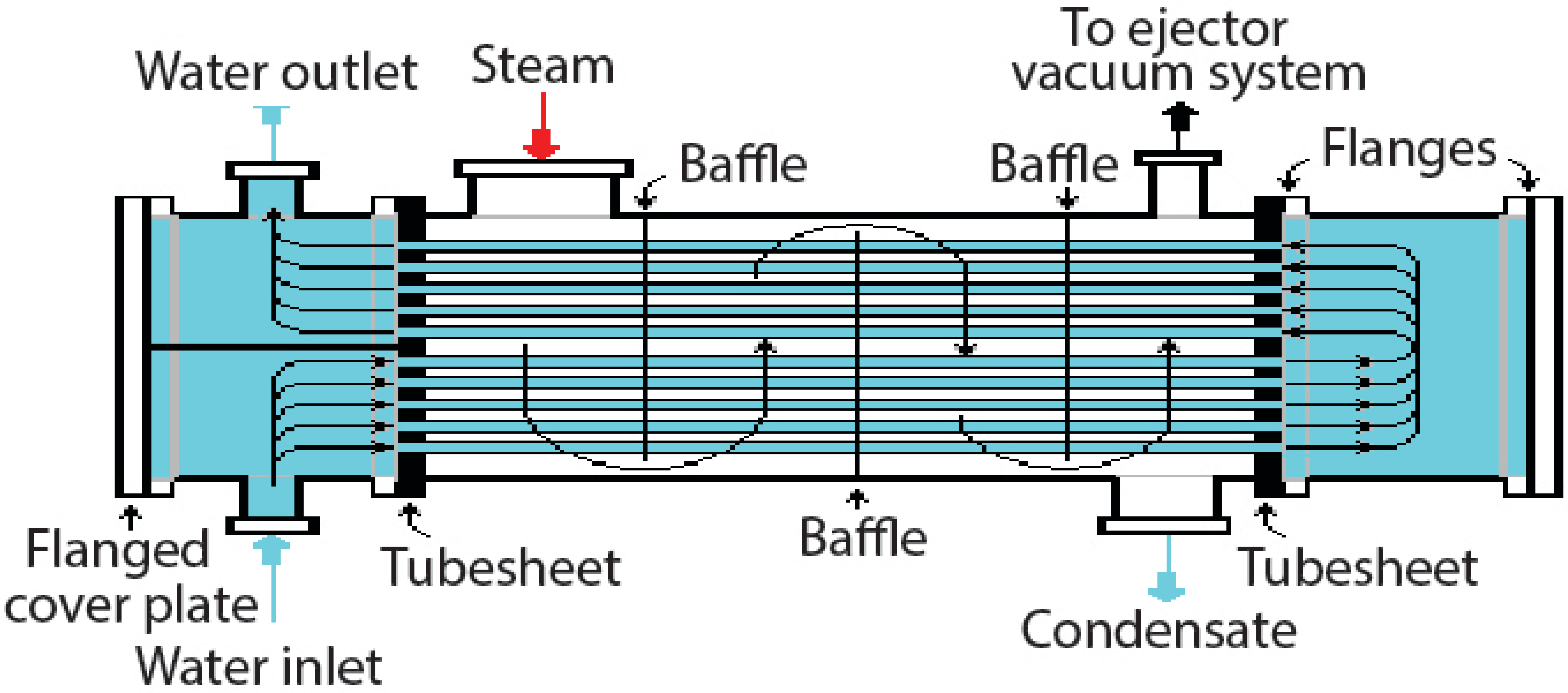
The Steam Turbine

- 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

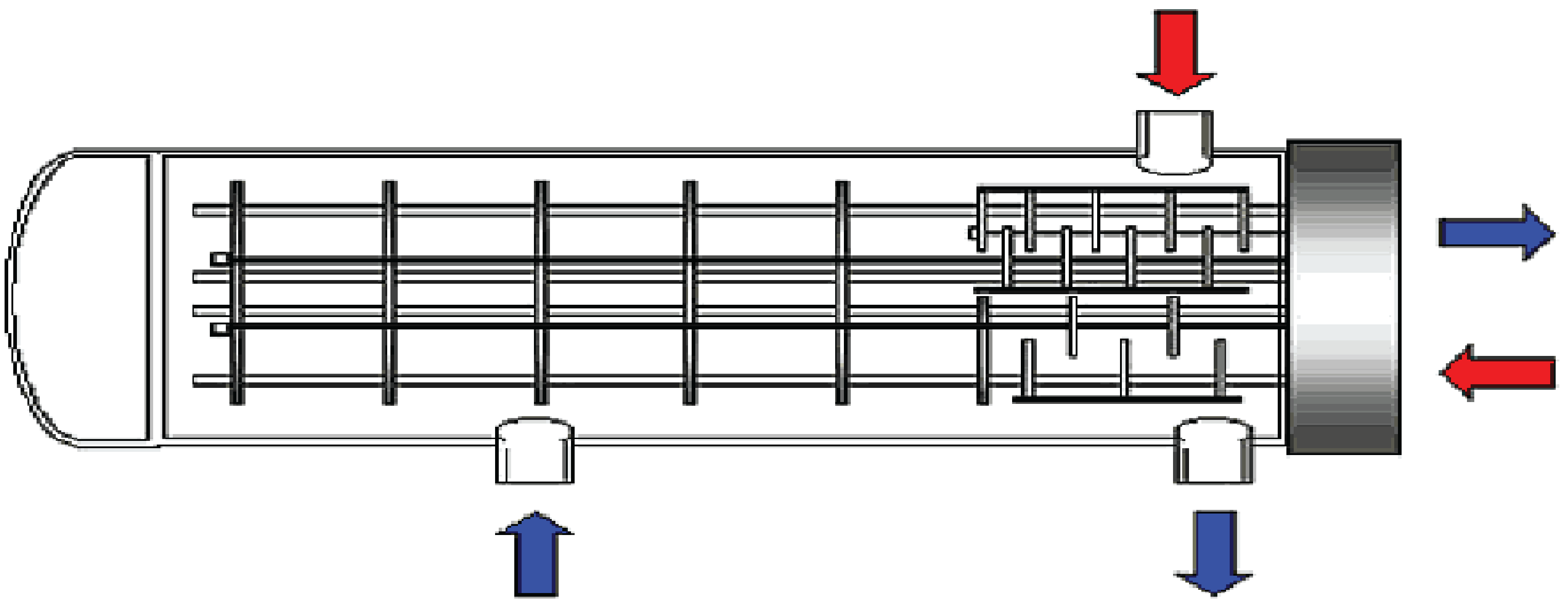
- Major Components
  - **Condenser:** Converts the exhaust steam into water after it leaves the last stage of the turbine
  - **Hotwell:** Receptacle where water is collected from the condenser
  - **Hotwell Make-up / Draw-off valves:** Compensate for losses or excesses to or from the condensate storage tank
  - **Demineralizers**: Clean up the condensate
  - **Condensate Pumps:** Move condensate up to the feedwater system
  - **Low Pressure Feedwater Heaters:** Preheats the condensate entering the deaerator/boiler feed pump
    - The plant may have multiple “strings” or series of feedwater heaters

Condenser

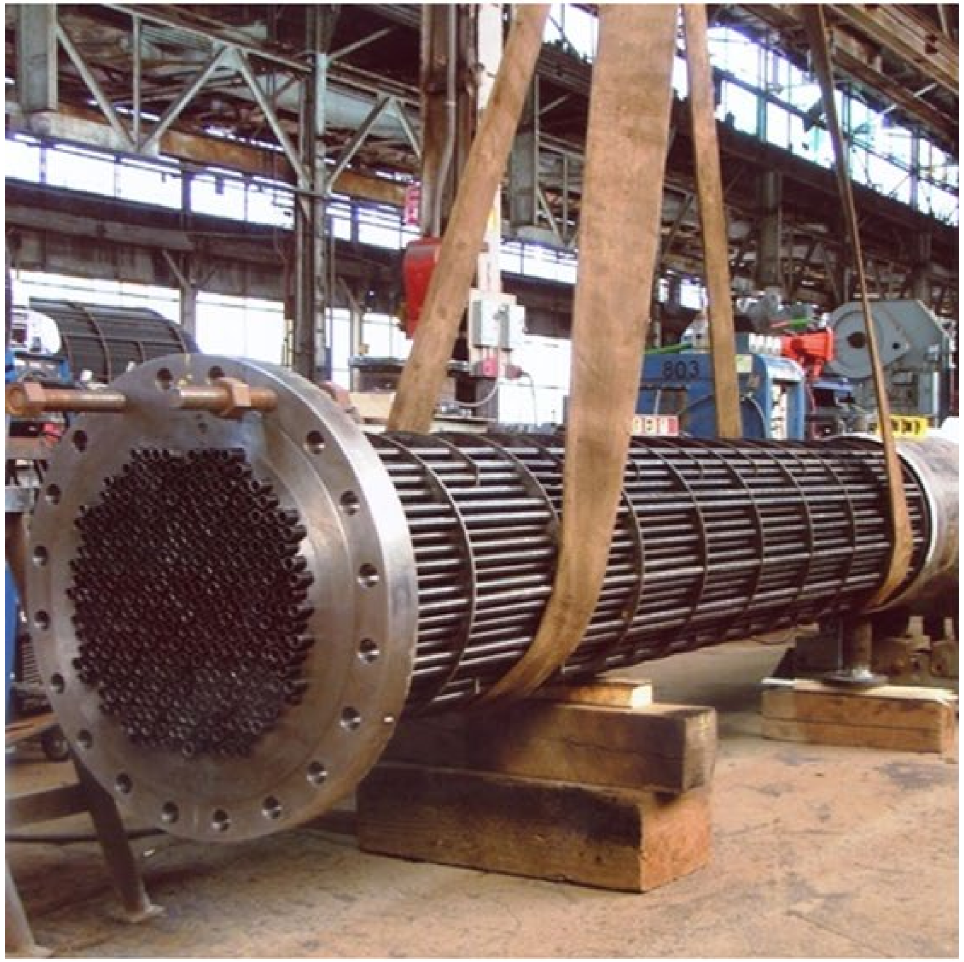


Water outlet
Steam
To ejector
vacuum system
Baffle
Baffle
Flanges
Flanged
cover plate
Water inlet
Tubesheet
Baffle
Tubesheet
Condensate

Condensate System – Feedwater Heater



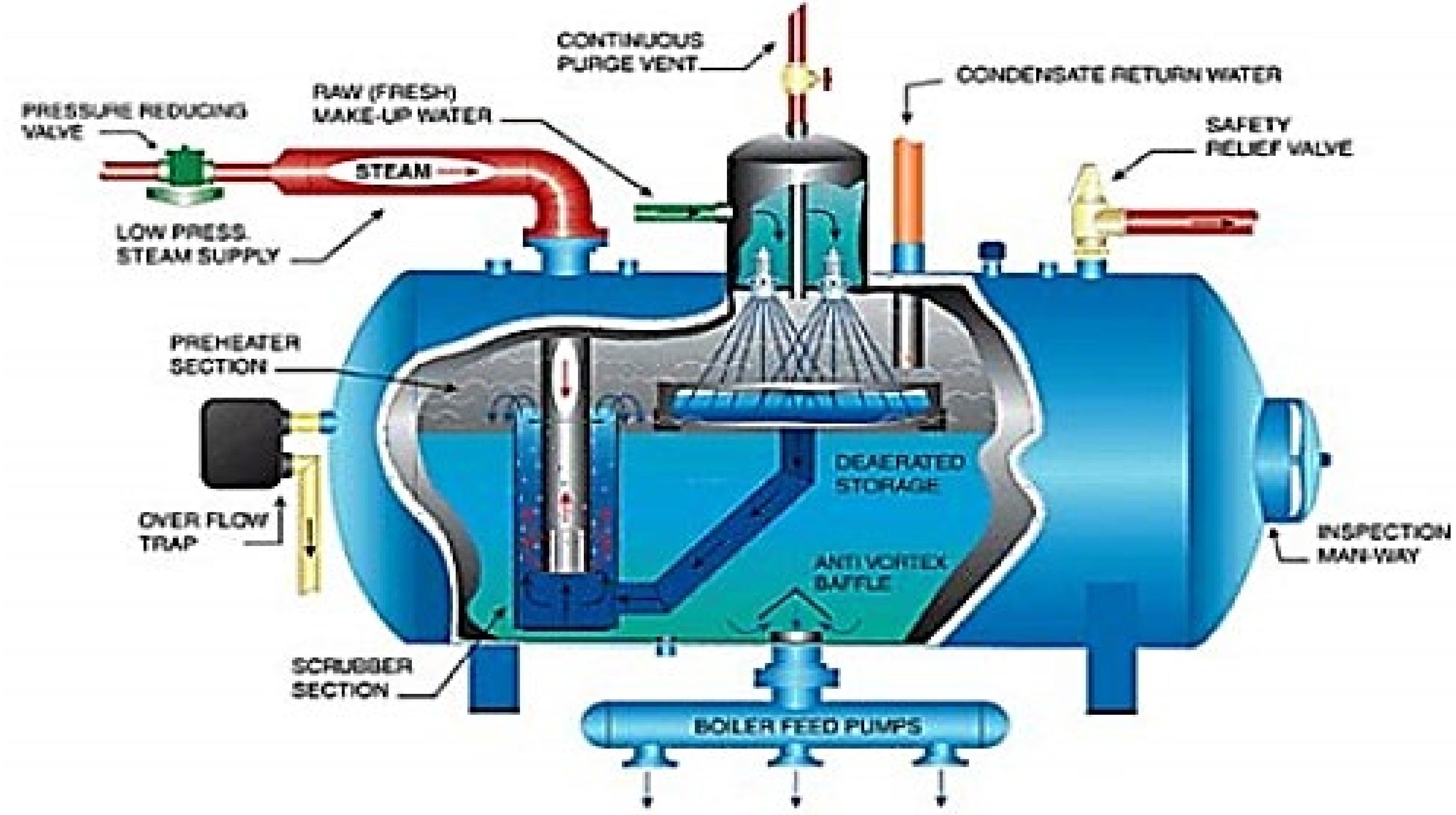
Condensate System – Feedwater Heater



The Feedwater System

- **Dearator:** Removes non-condensable gases (mainly oxygen) from the condensate
- **Boiler Feed Pump:** Supplies water to the boiler and has to overcome boiler pressure, friction in the heaters, piping, and economizer
- **High Pressure Feedwater Heaters:** Preheats the feedwater before entering the boiler
  - The plant may have multiple “strings” or series of Feedwater heaters

Condensate System - Deaerator



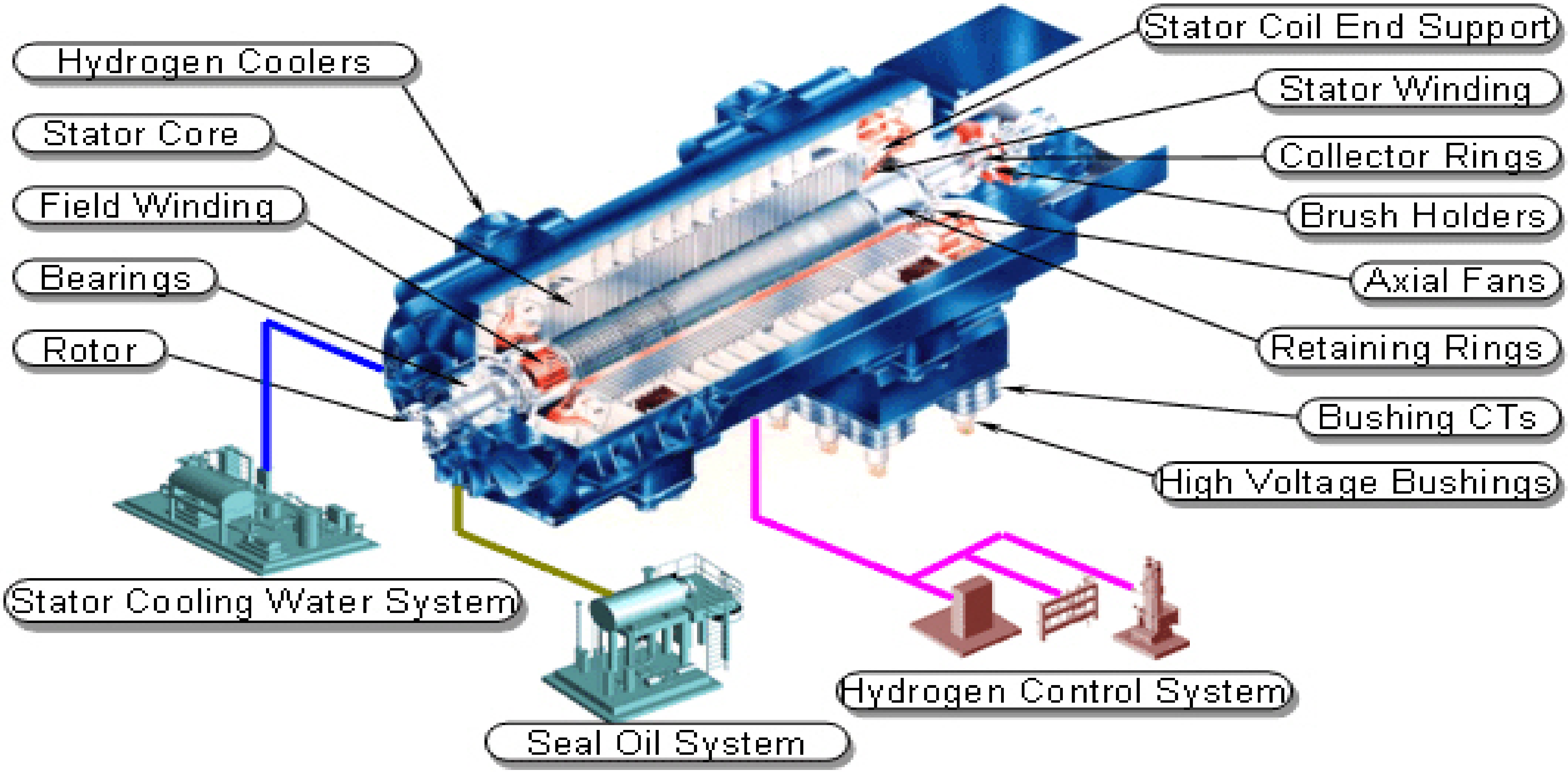
Condensate System - Deaerator

Start-Up Systems

- Prevent thermal stress damage
- Plant start-up systems provide a minimum flow path using main steam
- 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**


Hydrogen Coolers
Stator Core
Field Winding
Bearings
Rotor
Stator Coil End Support
Stator Winding
Collector Rings
Brush Holders
Axial Fans
Retaining Rings
Bushing CTs
High Voltage Bushings
Stator Cooling Water System
Seal Oil System
Hydrogen Control System

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

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

Fossil Generation

Generating Unit Principles of Operation

Fossil Conversion Process

Chemical Energy (Fuel)

to

Thermal Energy (Steam)

to

Mechanical Energy (Turbine)

to

Electrical Energy (Generator)

Fossil Generation - Types

- Fossil Plants include those powered primarily by Coal, Oil, Natural Gas, or a combination of these fuels
  - Coal-fired currently provide about 20.2% of the PJM area generation
  - 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 - Types

- Fossil Plants include those powered primarily by Coal, Oil, Natural Gas, or a combination of these fuels

IW

8  MW

Fossil Generation - Components

- In a fossil plant, the combustion of the fuel takes place within the **Boiler**
  - Basic functions of a boiler:
    - Pressure containment
    - Heat transfer
    - Steam separation
  - Two types of boilers:
    - Subcritical (drum type)
    - Supercritical

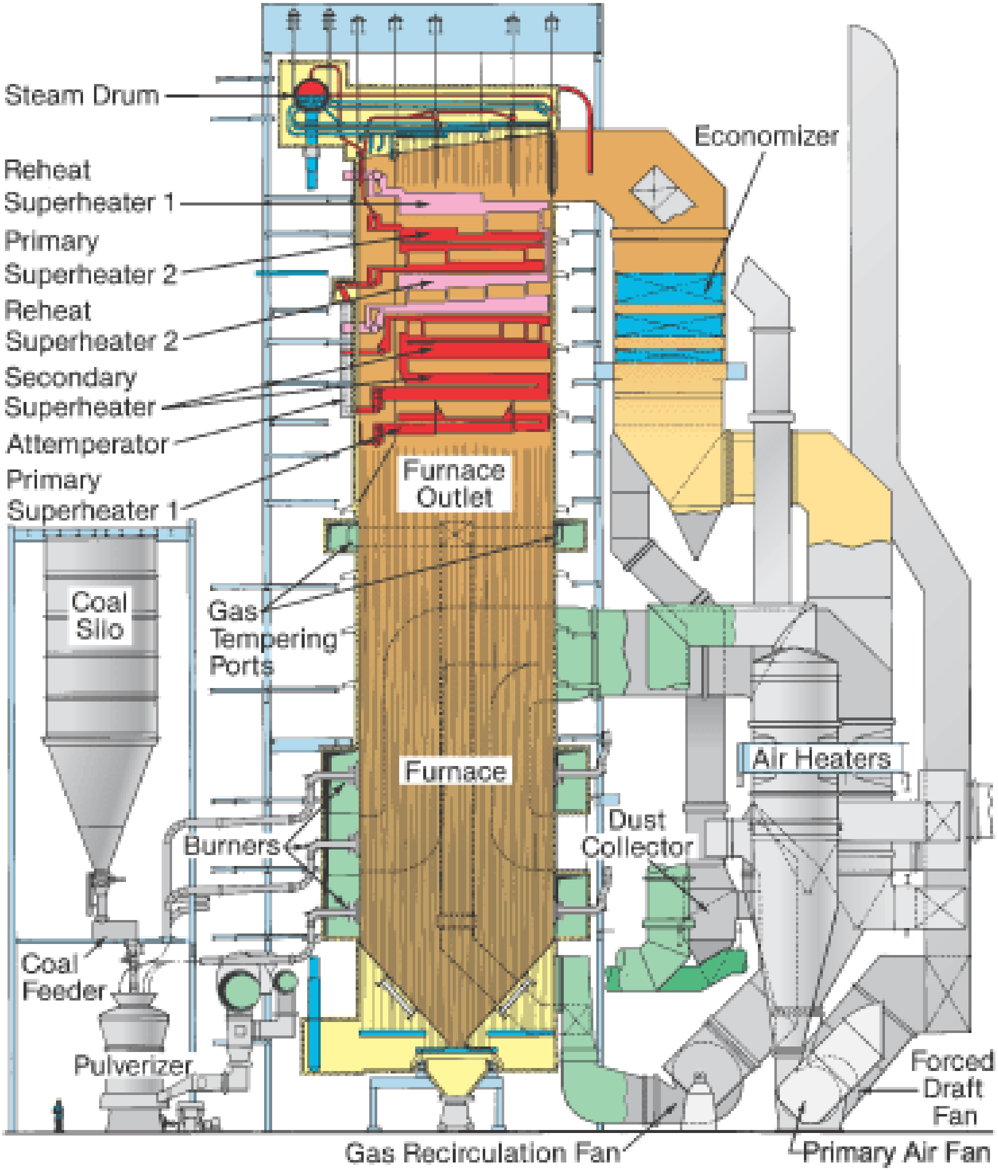
Fossil Generation - Components

- Drum Type Boilers - 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 – raises 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



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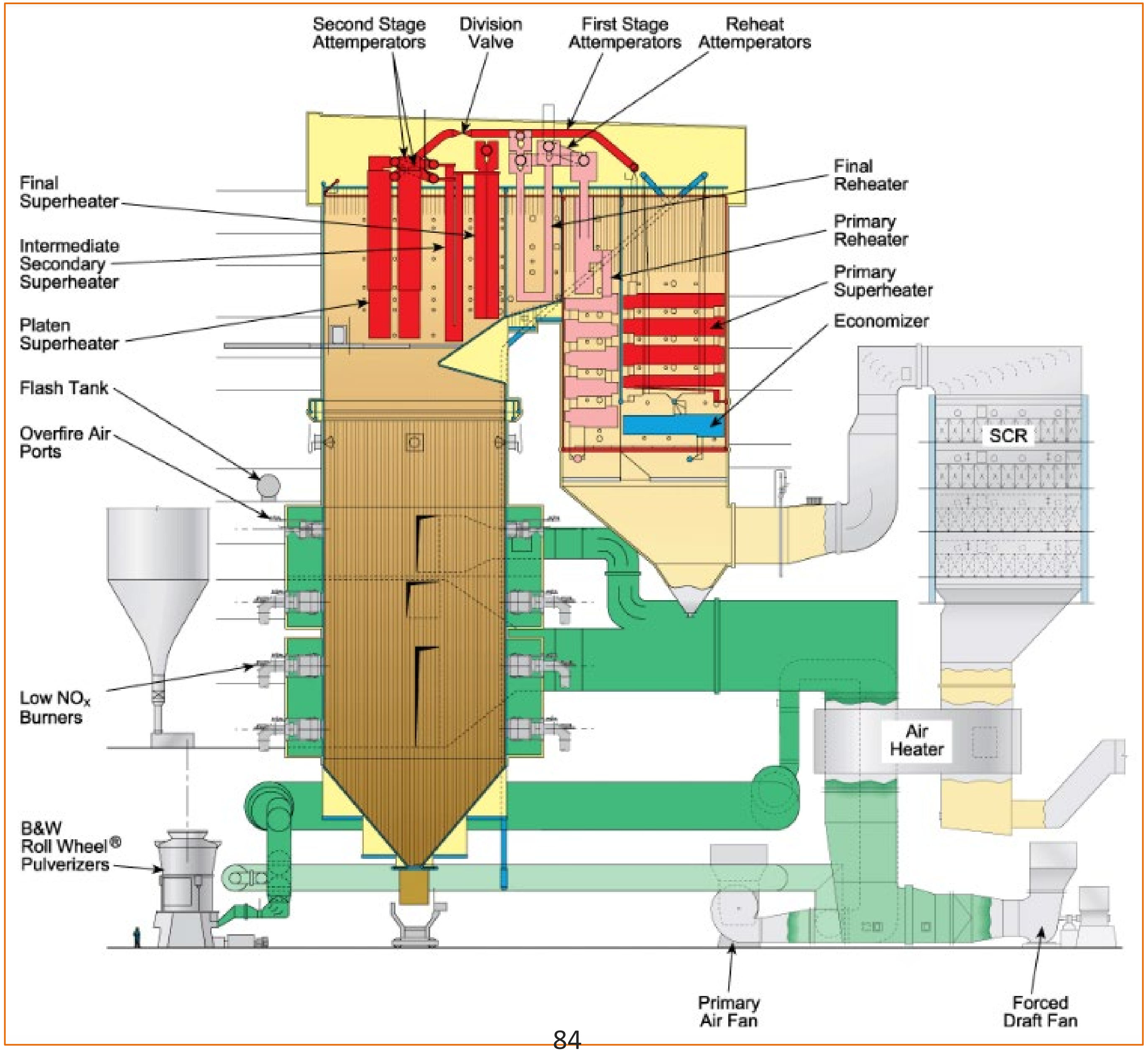
Principles of Operation

- Super Critical Boiler
  - No boiler drum
    - Water to steam within the water wall tubes
  - Consists of many circuits of superheaters
  - Operates in excess of 3206.2 PSIA / 705.4 F
  - No recirculation process- “Once Through”
  - 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

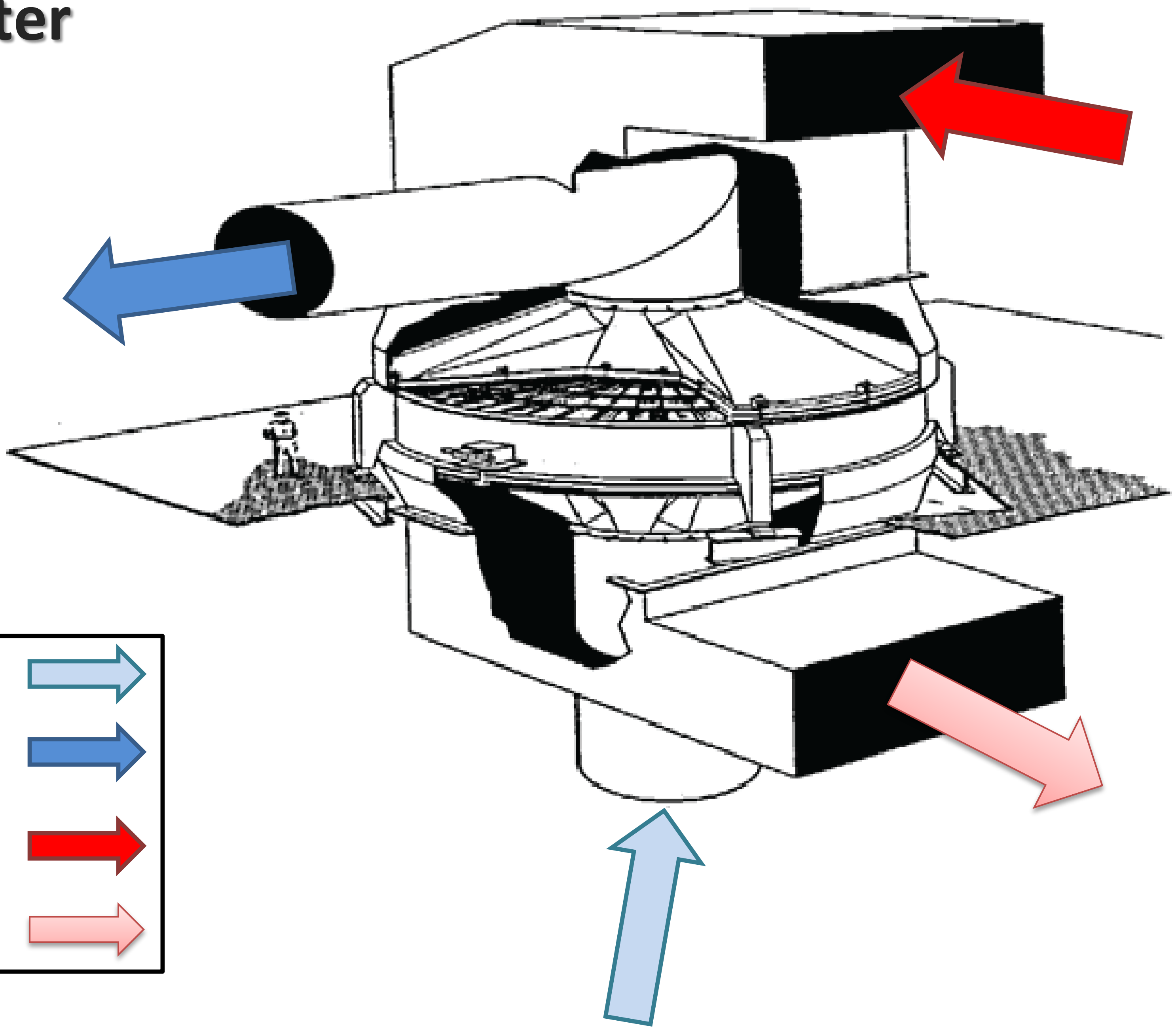
Fossil Generation

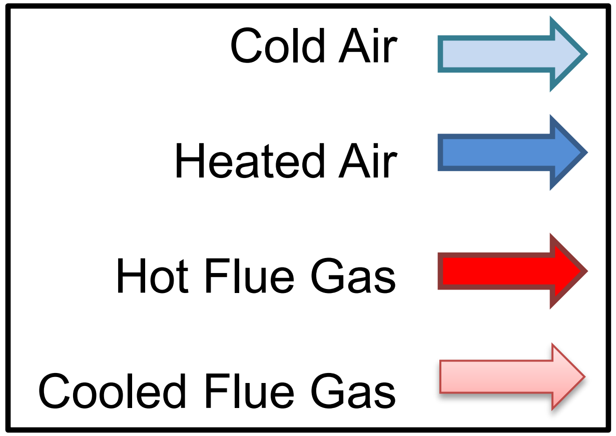


Fossil Generation - Components

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

Air Preheater





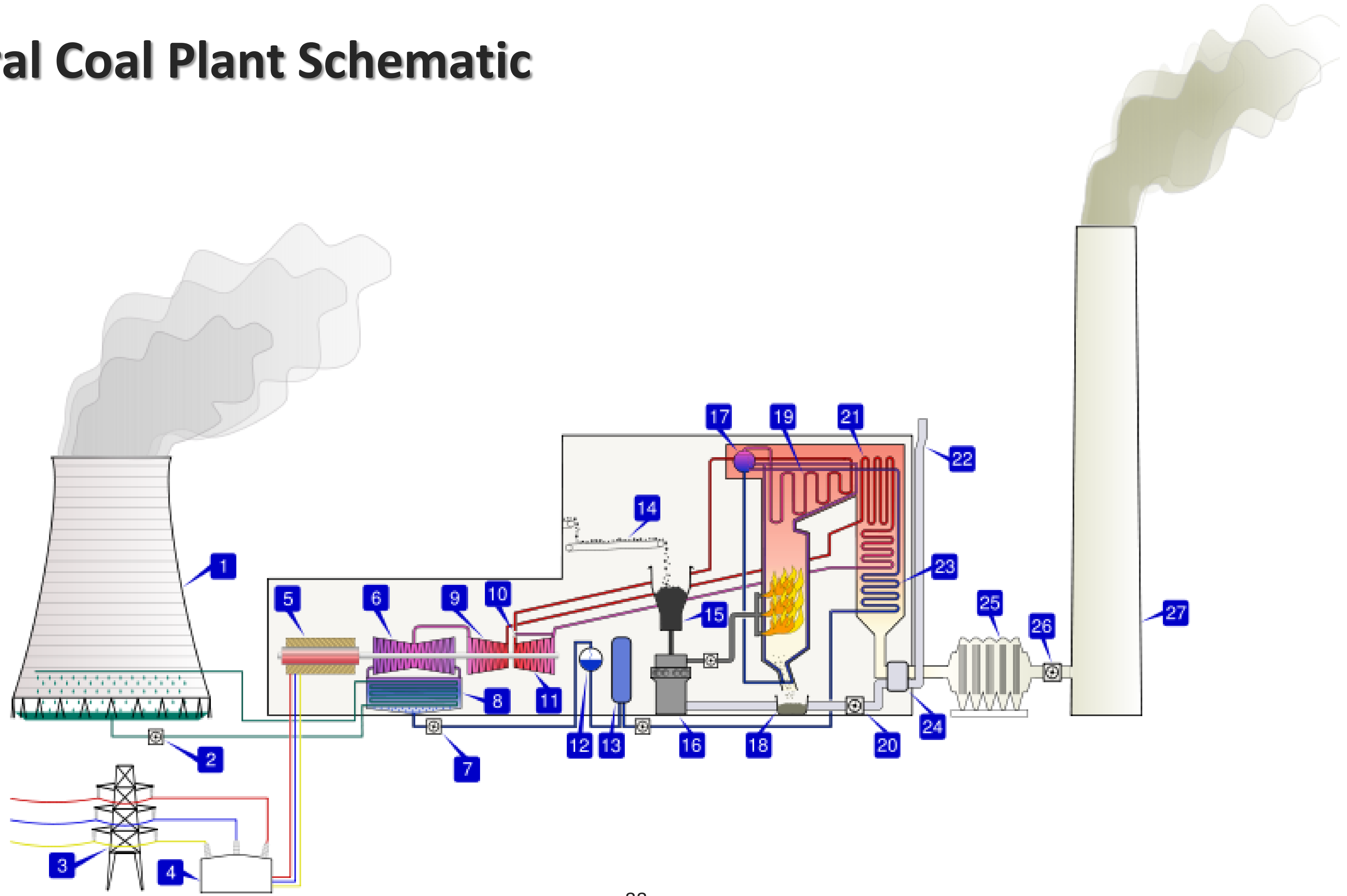
Miscellaneous Fossil Plant Systems

- **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

General Coal Plant Schematic



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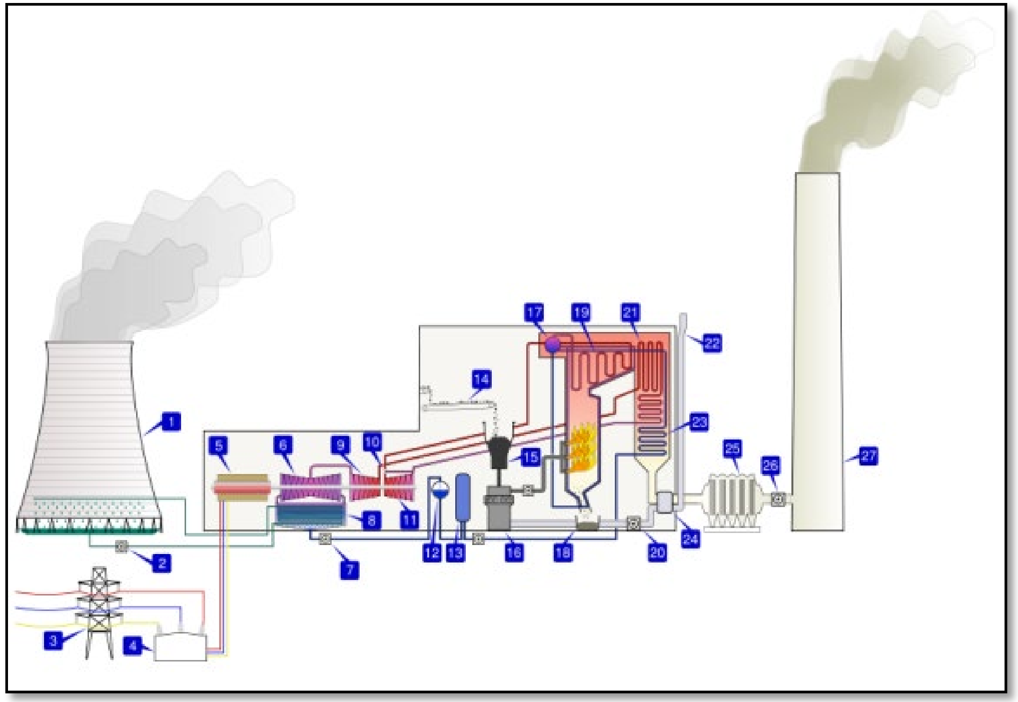
Key

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



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, SO)
  - Disadvantages
    - Long start-up time
    - Expensive to build (greater press. / temp.)
    - Loss of circulation causes serious boiler damage

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

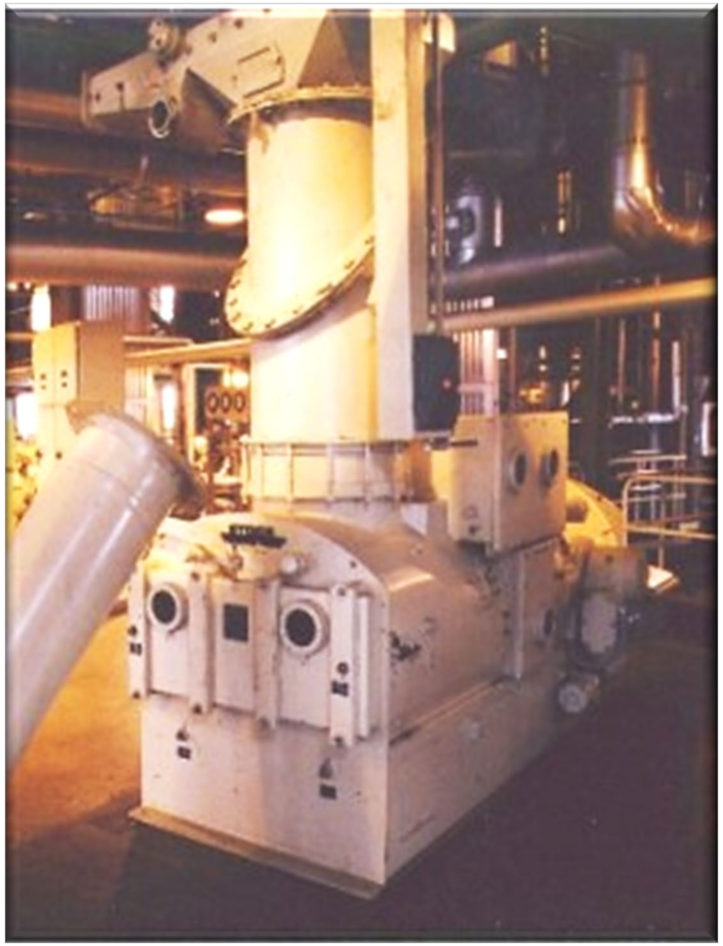
- Auxiliary equipment outages (scheduled or unscheduled)
  - Heaters, condensate or boiler feed pumps
  - Pulverizers (Mills) or oil pumps, gas
  - Fans: ID, FD, or primary air
  - Pumps: circulating water
  - Fuel
  - Ash handling

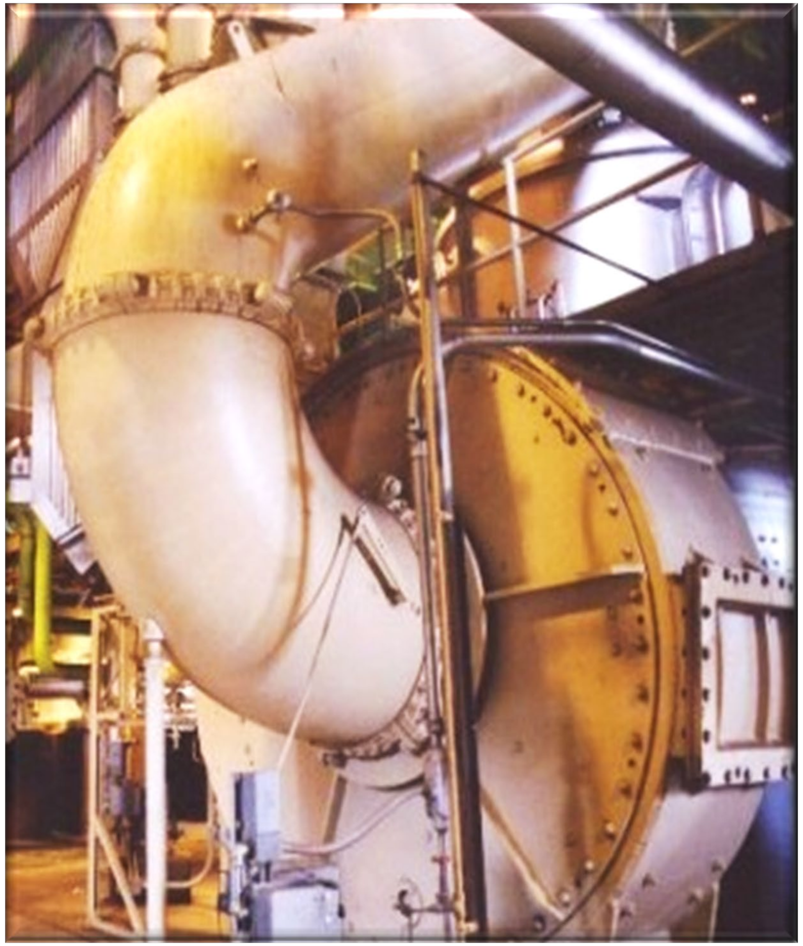
Fossil Unit Limitations That May Affect Power Output

Fuel Limitations - Coal Issues:

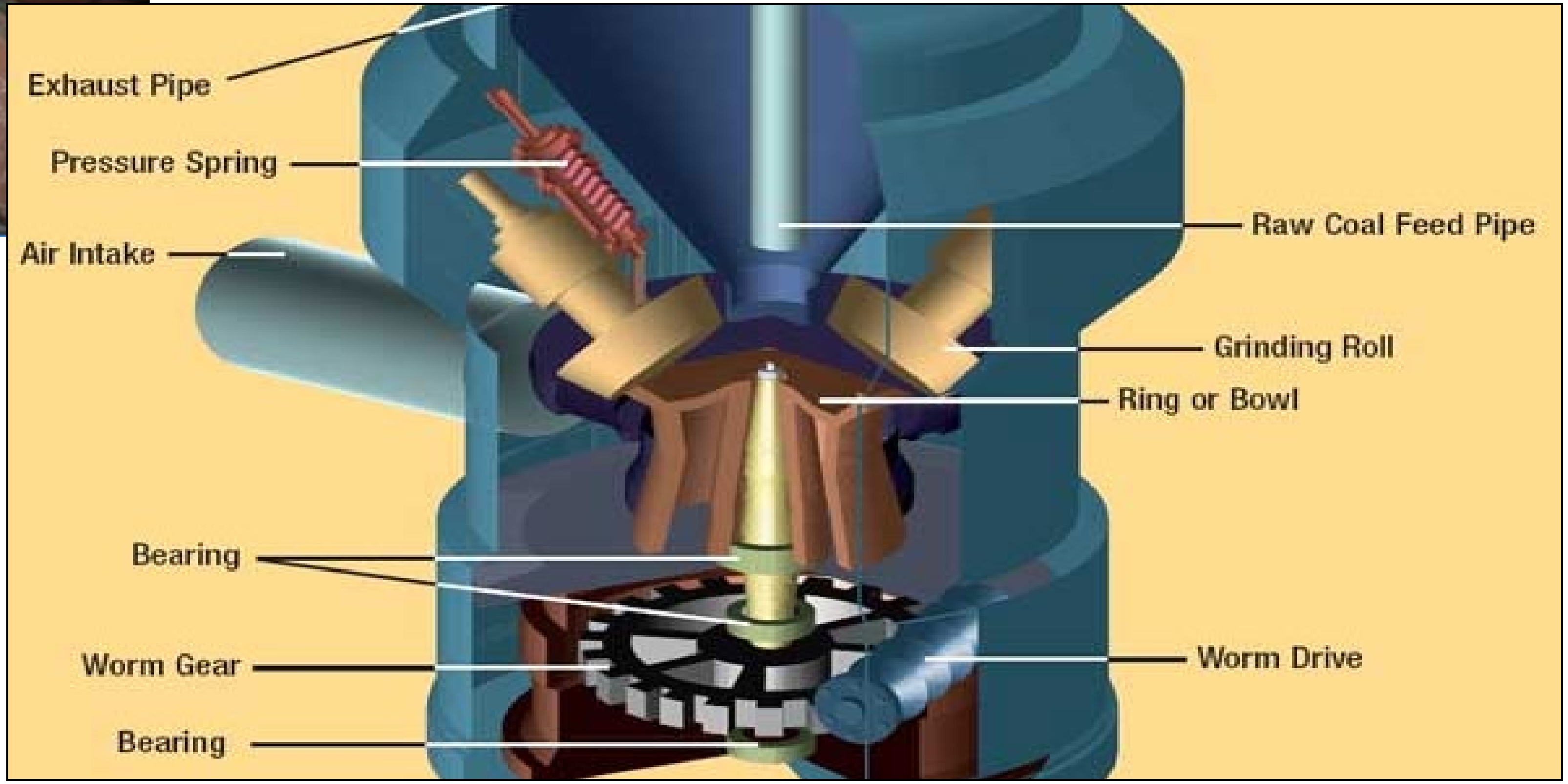
- Excessive moisture or bad weather can lead to;
  - Difficulty unloading
  - Sliding on conveyor belts
  - Build-up in chutes
  - Frozen coal
- Poor quality coal can lead to increases in slagging and high ash resistivity
- Coal must be crushed or pulverized to burn efficiently
  - Degree of crushing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

Pulverizer Mill





Pulverizer Mill



Fossil Unit Limitations That May Affect Power Output

- Fuel Limitations - 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/guns need to be cleaned and maintained regularly

Fossil Unit Limitations That May Affect Power Output

- Fuel Limitations - 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

Nuclear Generation

Generating Unit Principles of Operation

Nuclear Conversion Process

Nuclear Energy (Fission)

to

Thermal Energy (Steam)

to

Mechanical Energy (Turbine)

to

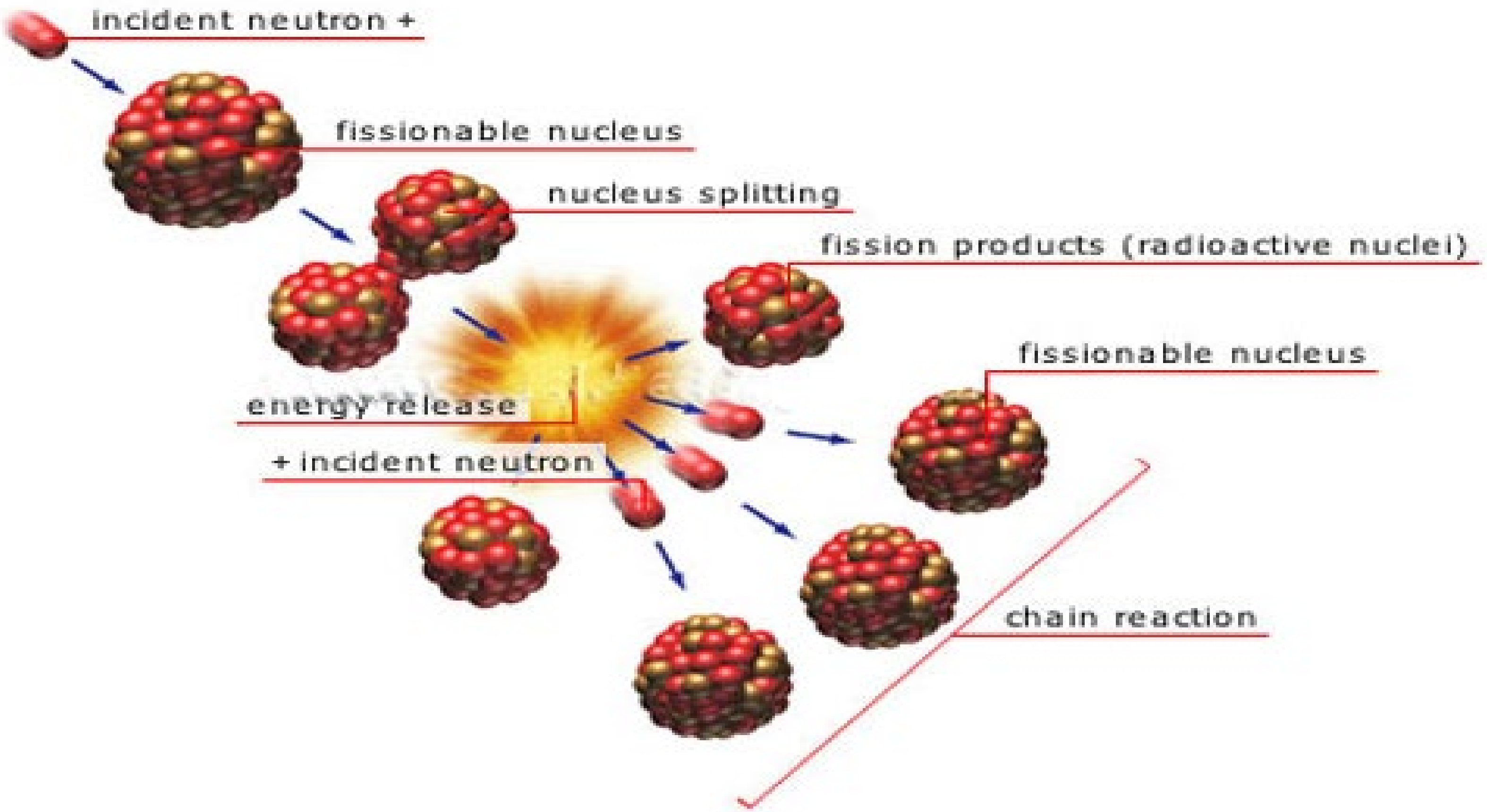
Electrical Energy (Generator)

Nuclear Generation

- Nuclear Fission yields the highest amount of energy produced per mass of fuel “consumed” for any existing fuel type
- 32.7% 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 enriched uranium, U235

Nuclear Generation

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



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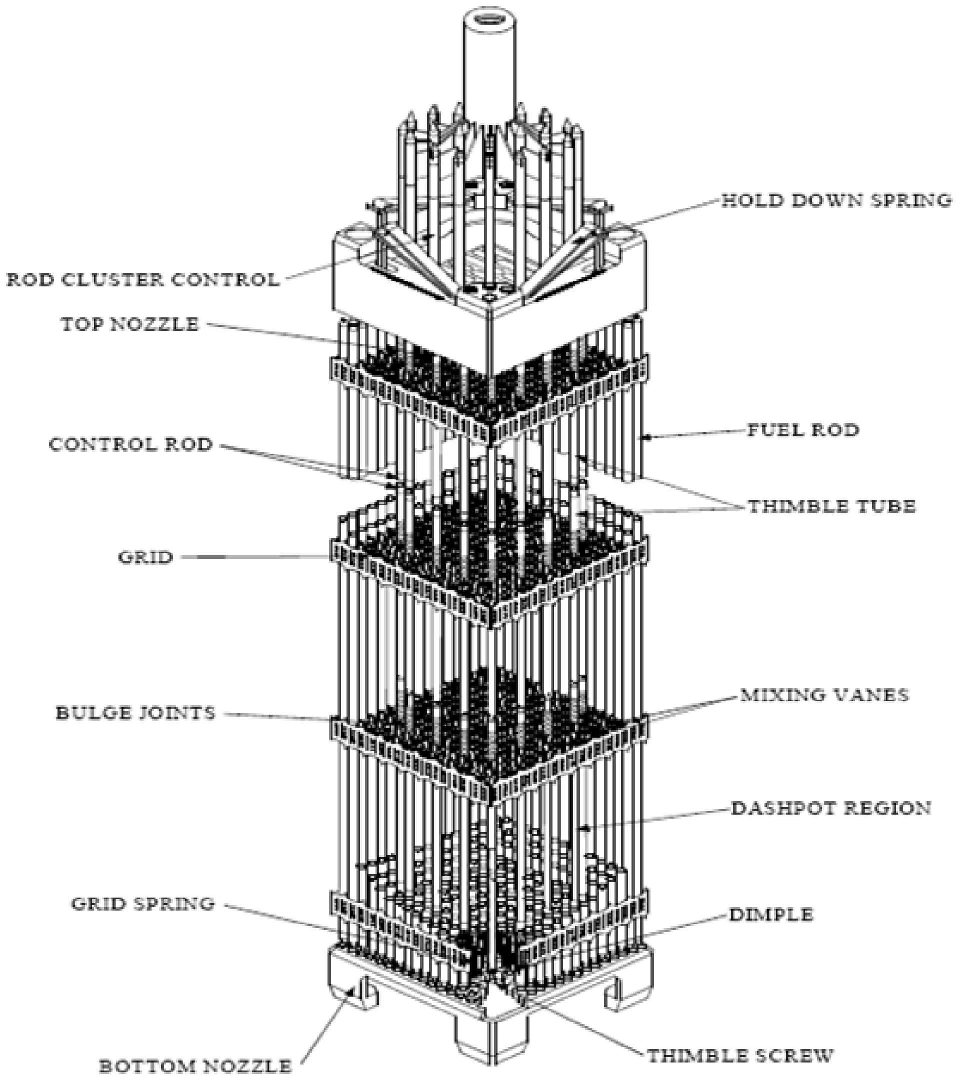
Nuclear Generation

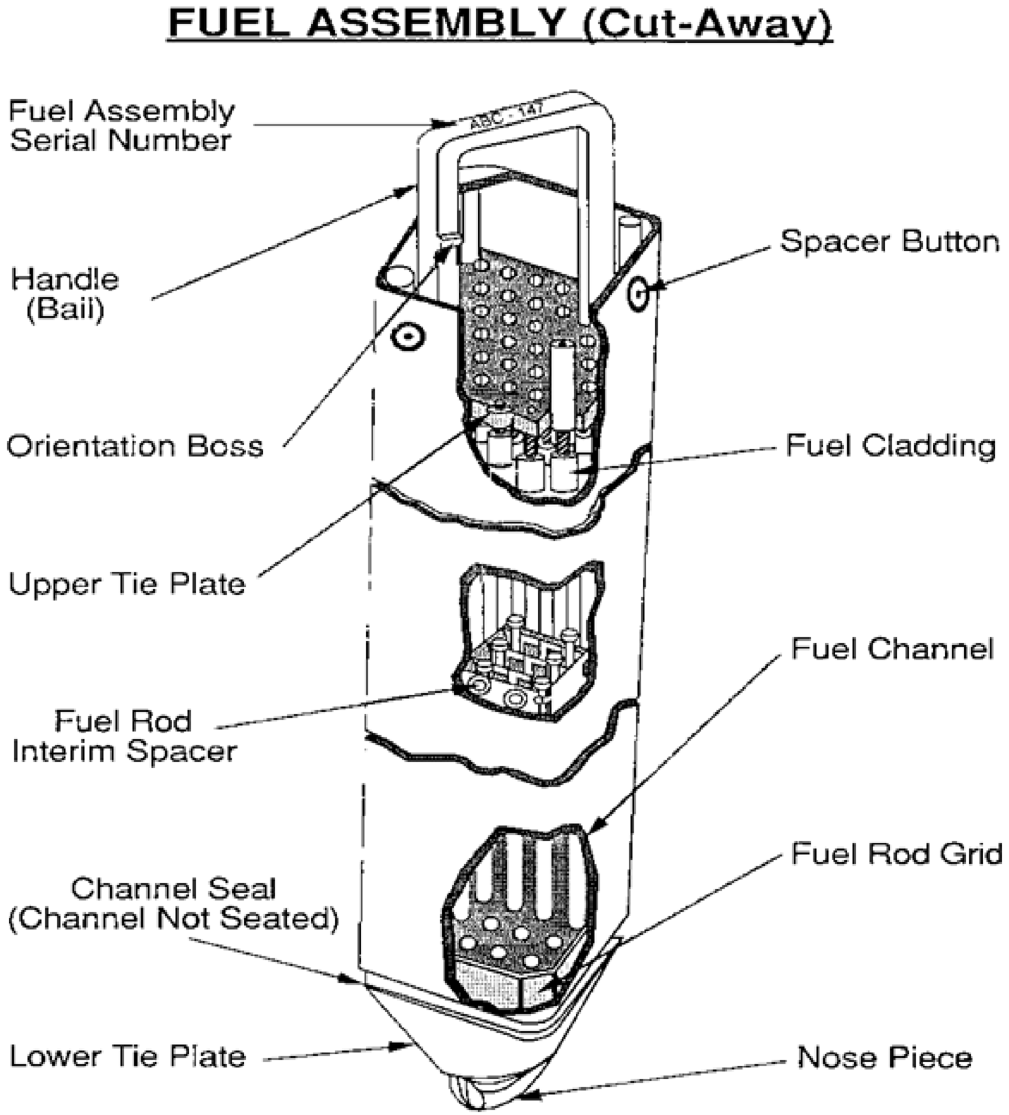
- Fuel is loaded at 3.5% 235U and replaced once the concentration has fallen to 1.2%
- 1000 MW nuclear plant: ~30 tons of fuel per year vs. 1000 MW coal plant: 9,000 tons of coal per day
- In a light water reactor, water is used as both the **Moderator** and the **Coolant**

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
  - **Fuel Channel** – surrounds BWR Fuel Assemblies to provide more surface areas for steam bubble formation

Fuel Assembly





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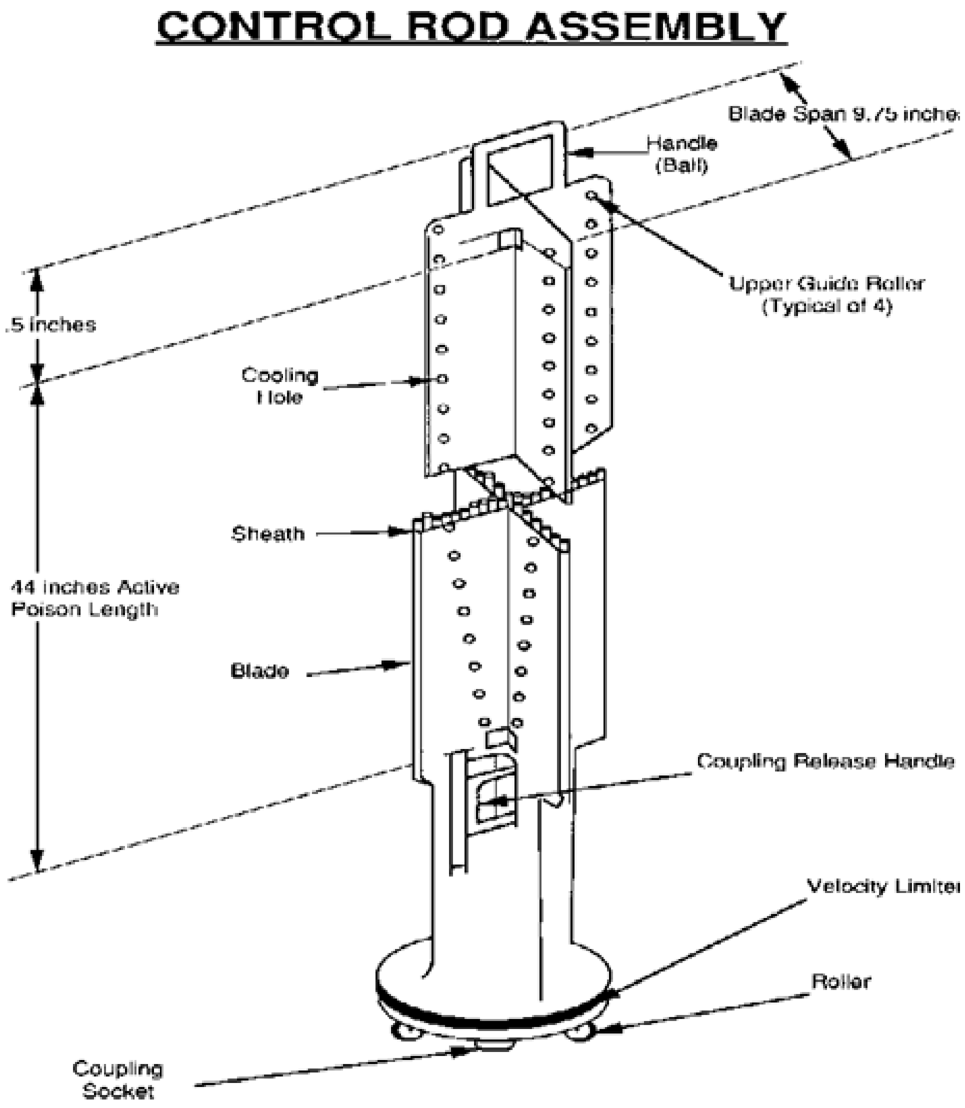
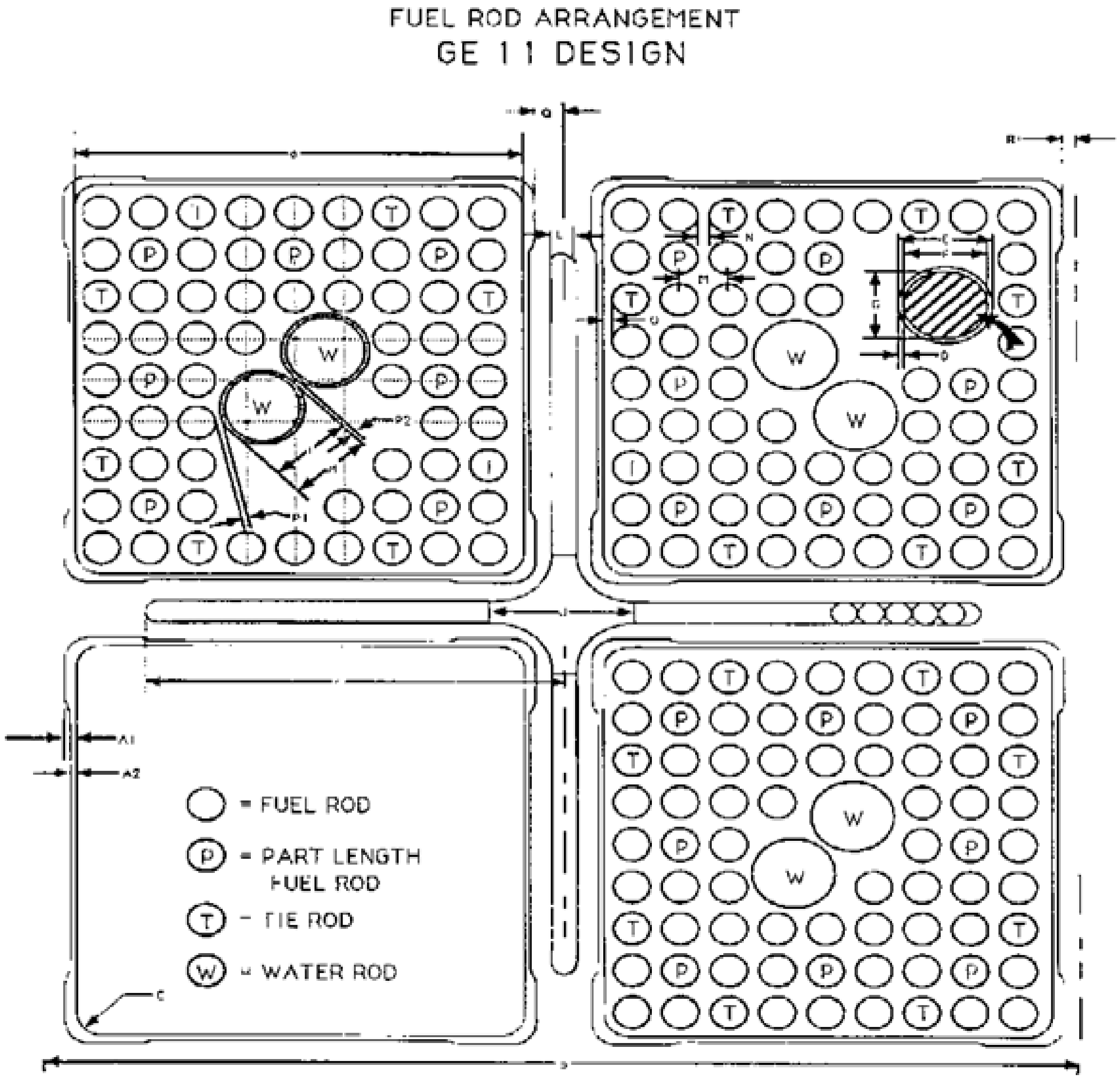
Control Rod



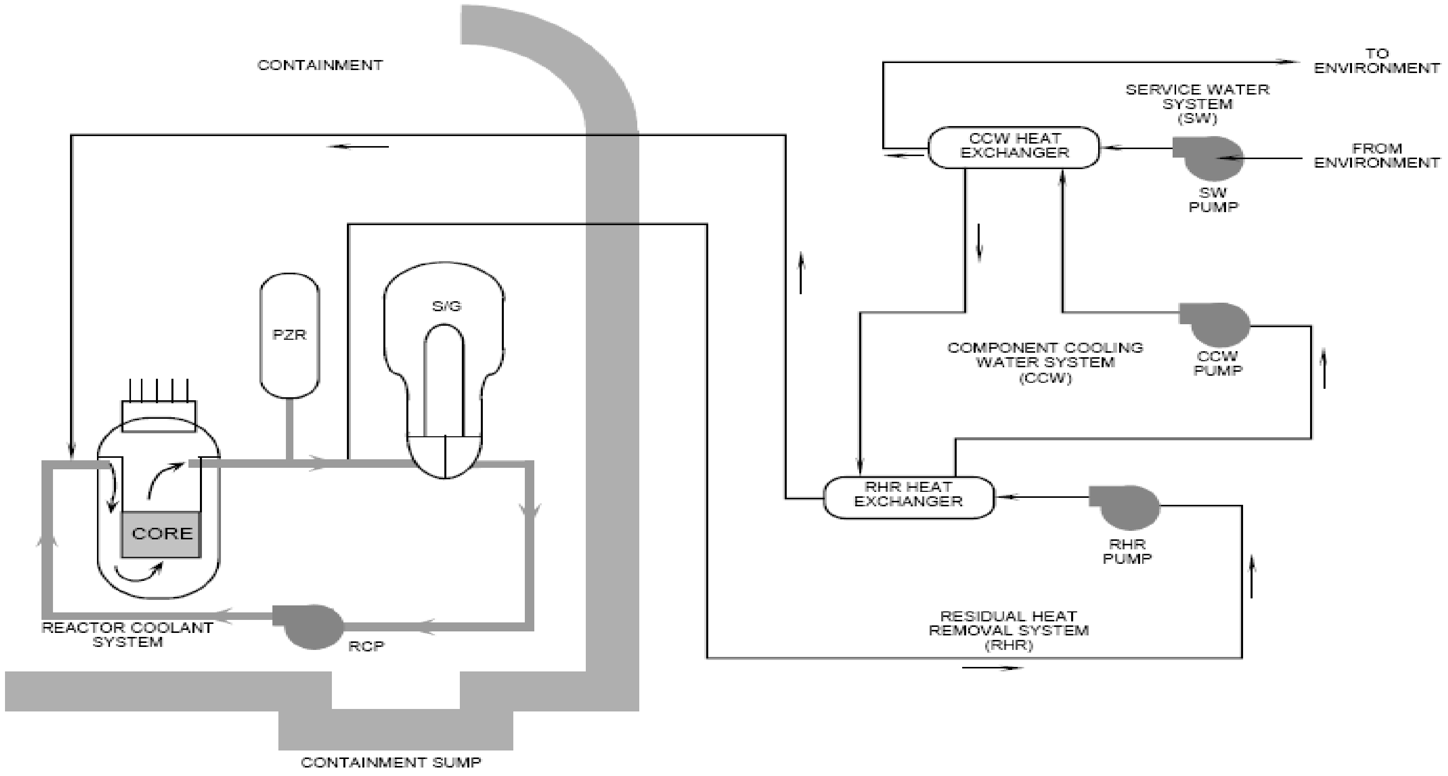
CONTROL ROD ASSEMBLY
Blade Span 9.75 inche
Handle
(Ball)
Upper Guide Roller
(Typical of 4)
.5 inches
Cooling
Hole
Sheath
44 inches Active
Poison Length
Blade
Coupling Release Handle
Velocity Limiter
Roller
Coupling
Socket



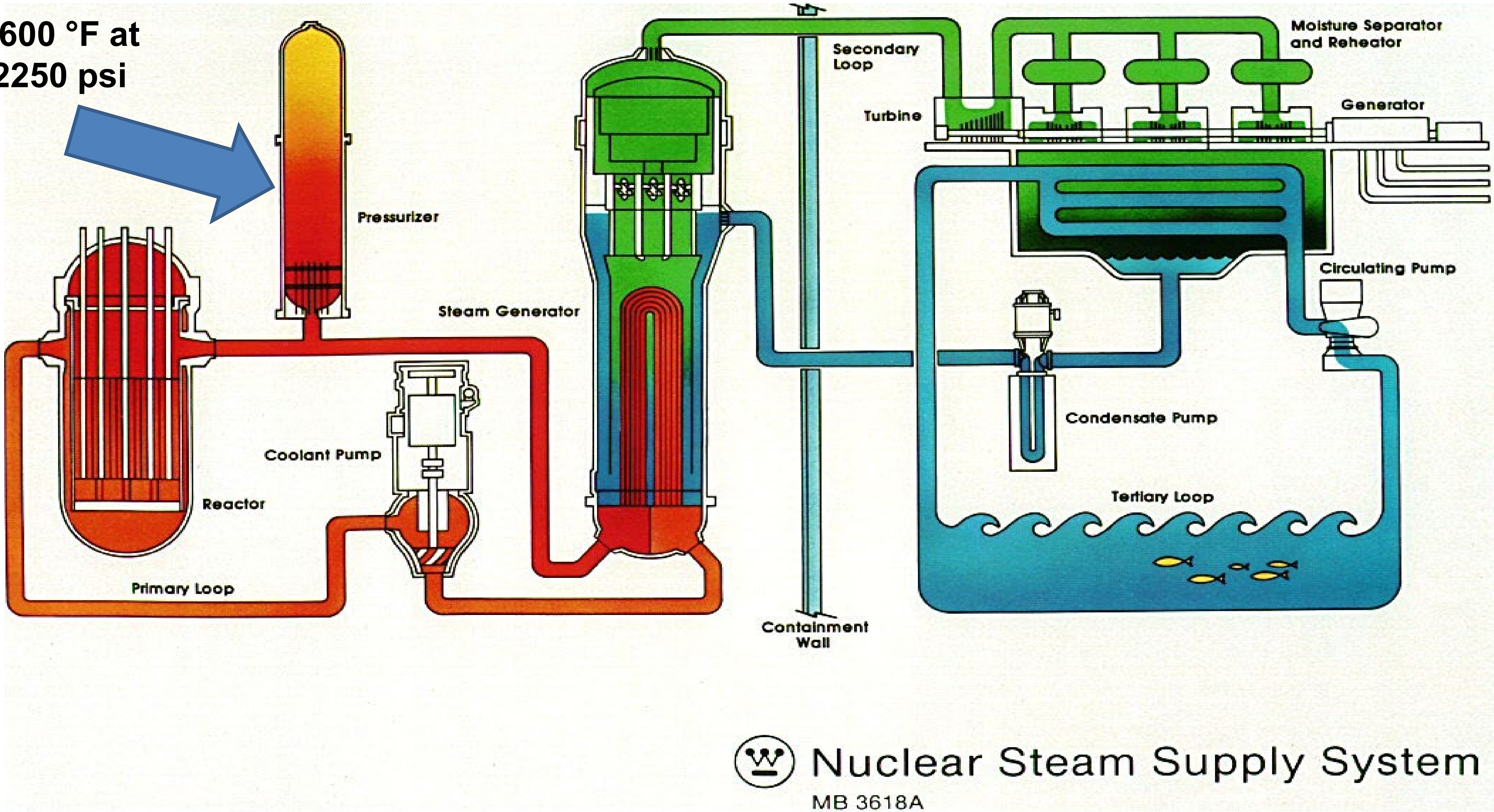
FUEL ROD ARRANGEMENT
GE 11 DESIGN
= FUEL ROD
= PART LENGTH
FUEL ROD
= TIE ROD
= WATER ROD

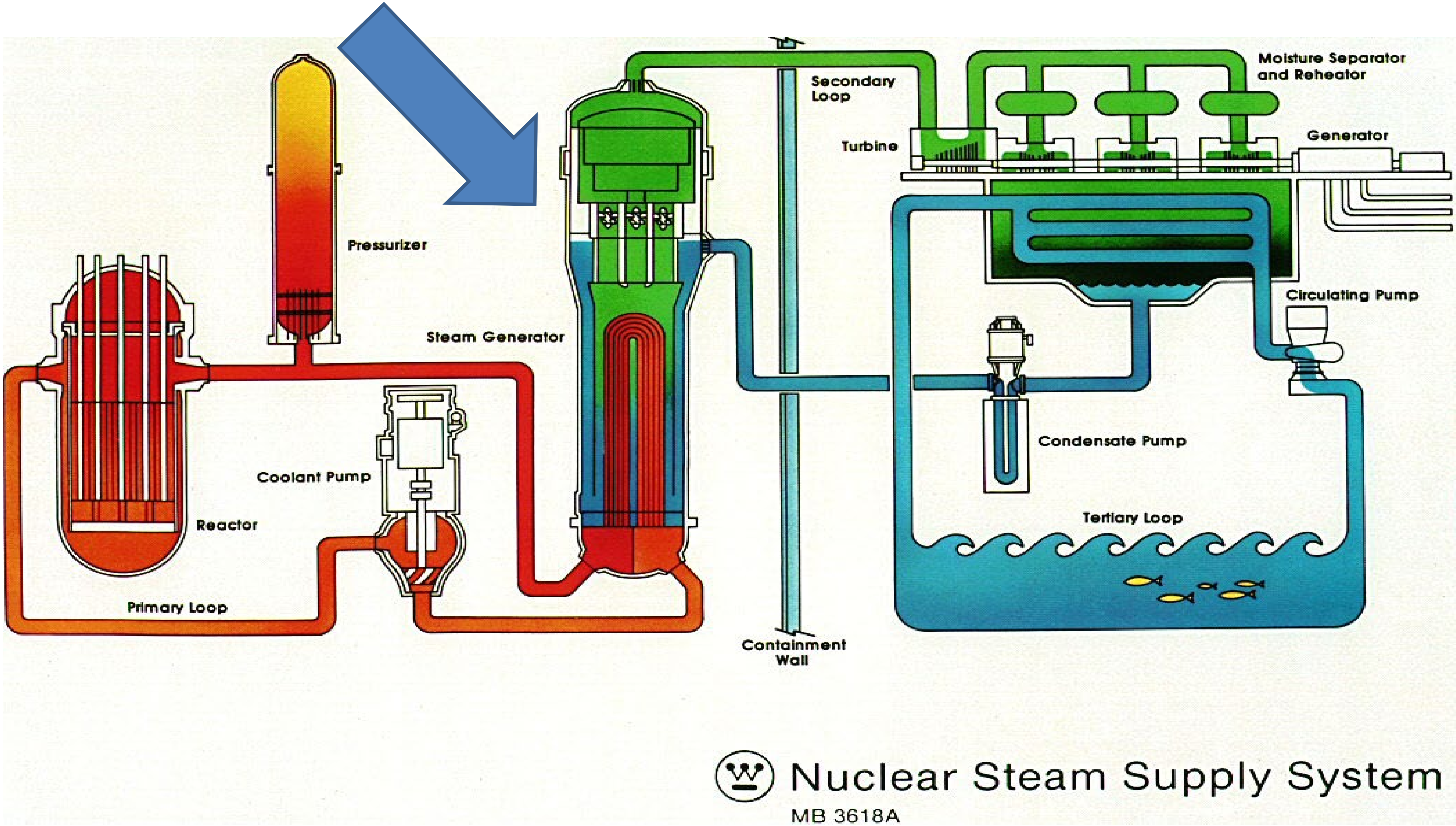
Systems Common to Both Designs

- **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

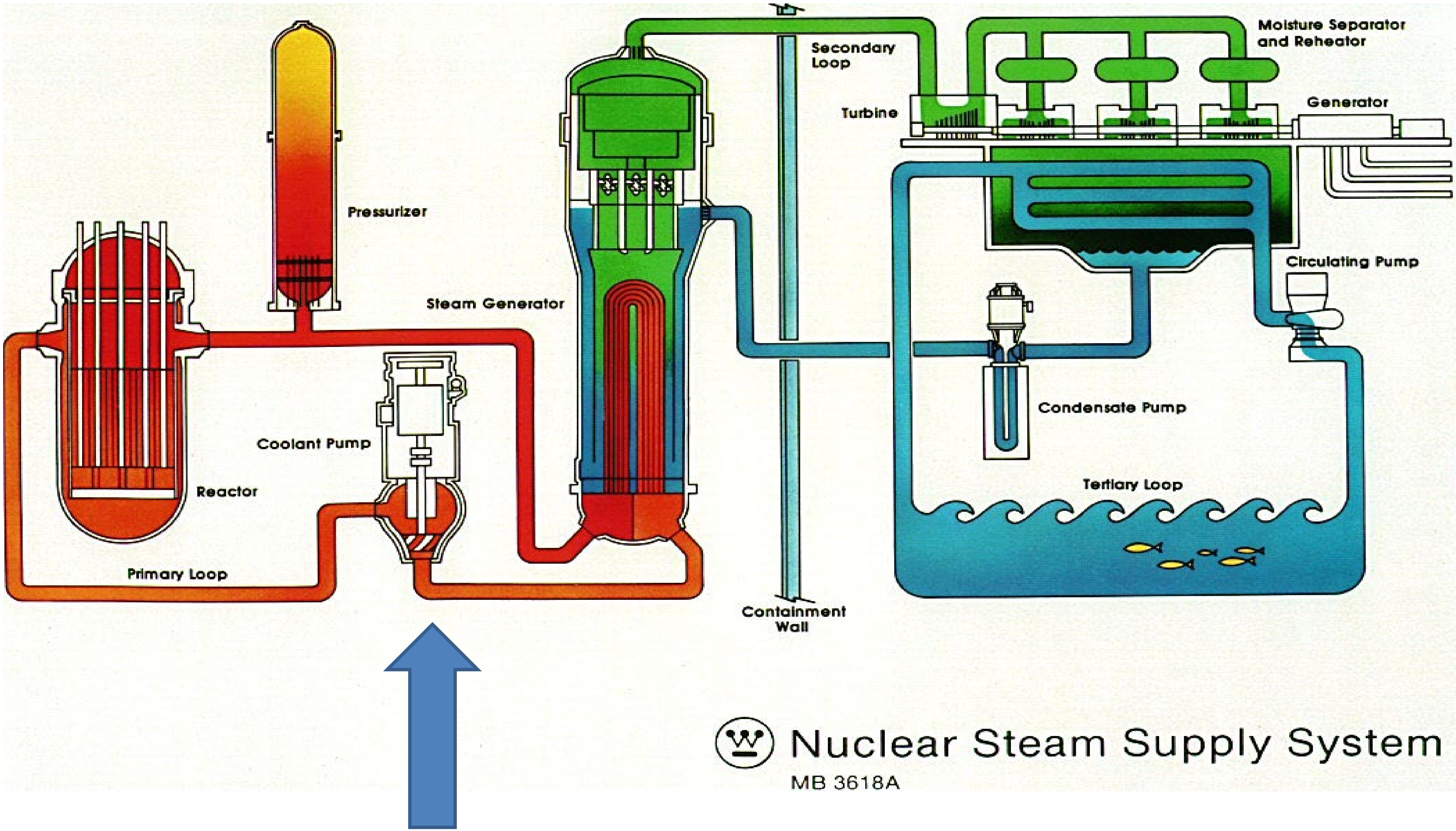


~600 °F at 2250 psi





Moisture Separator and Reheater
Secondary Loop
Turbine
Generator
Pressurizer
Steam Generator
Circulating Pump
Coolant Pump
Condensate Pump
Reactor
Tertiary Loop
Primary Loop
Containment Wall
Nuclear Steam Supply System
MB 3618A


Moisture Separator
and Reheator
Secondary
Loop
Turbine
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Pressurizer
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Wall
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MB 3618A

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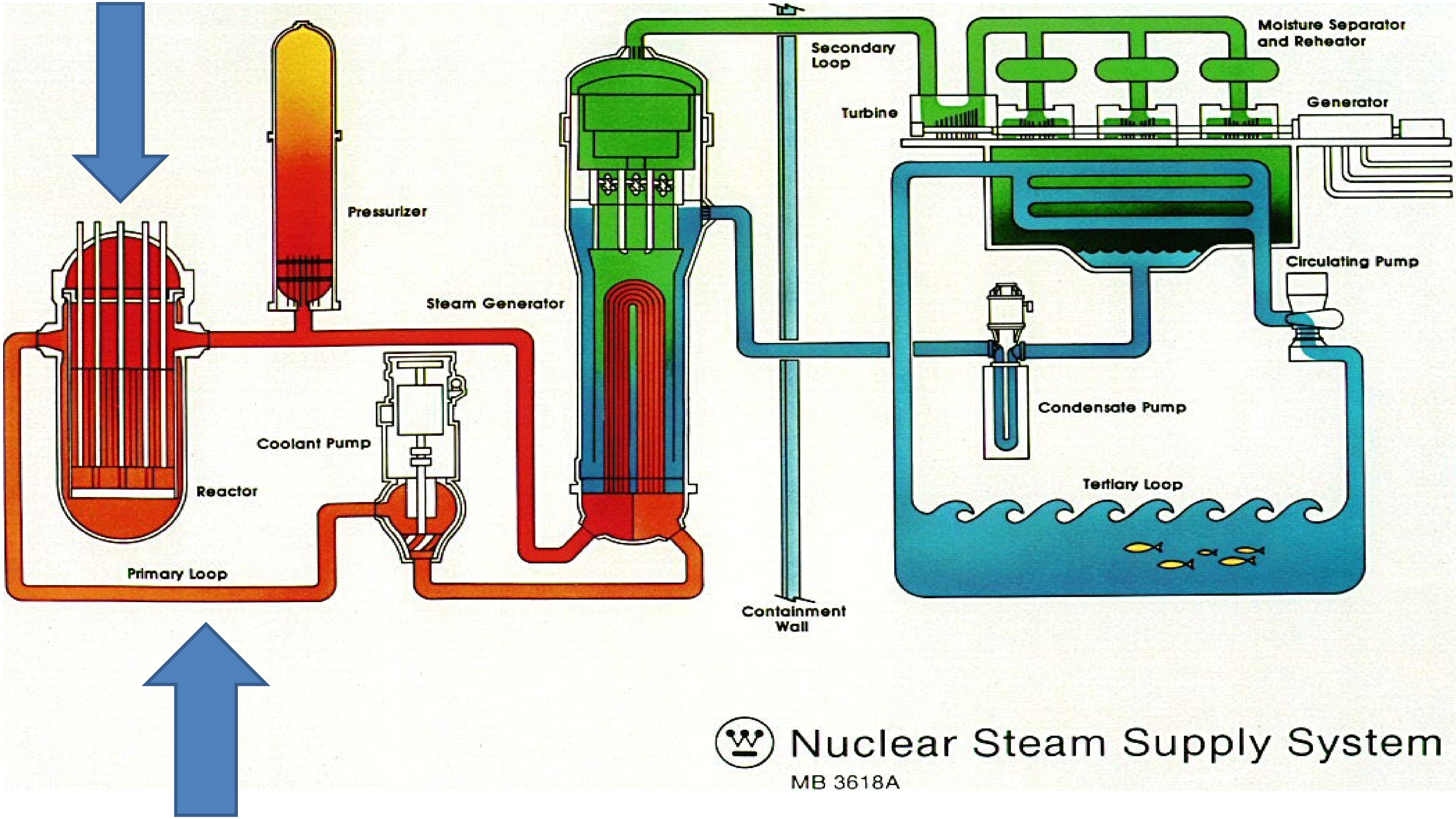
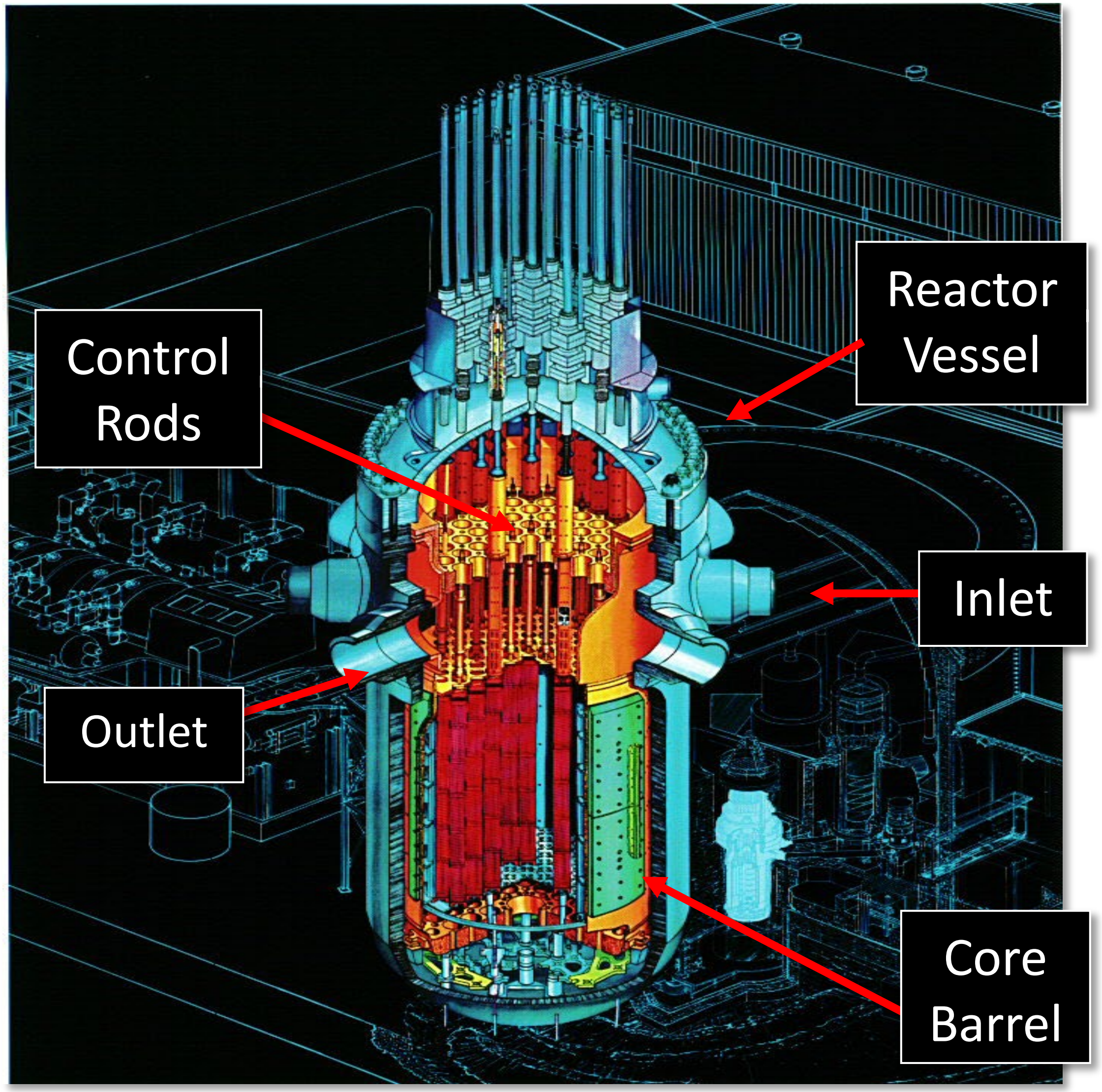
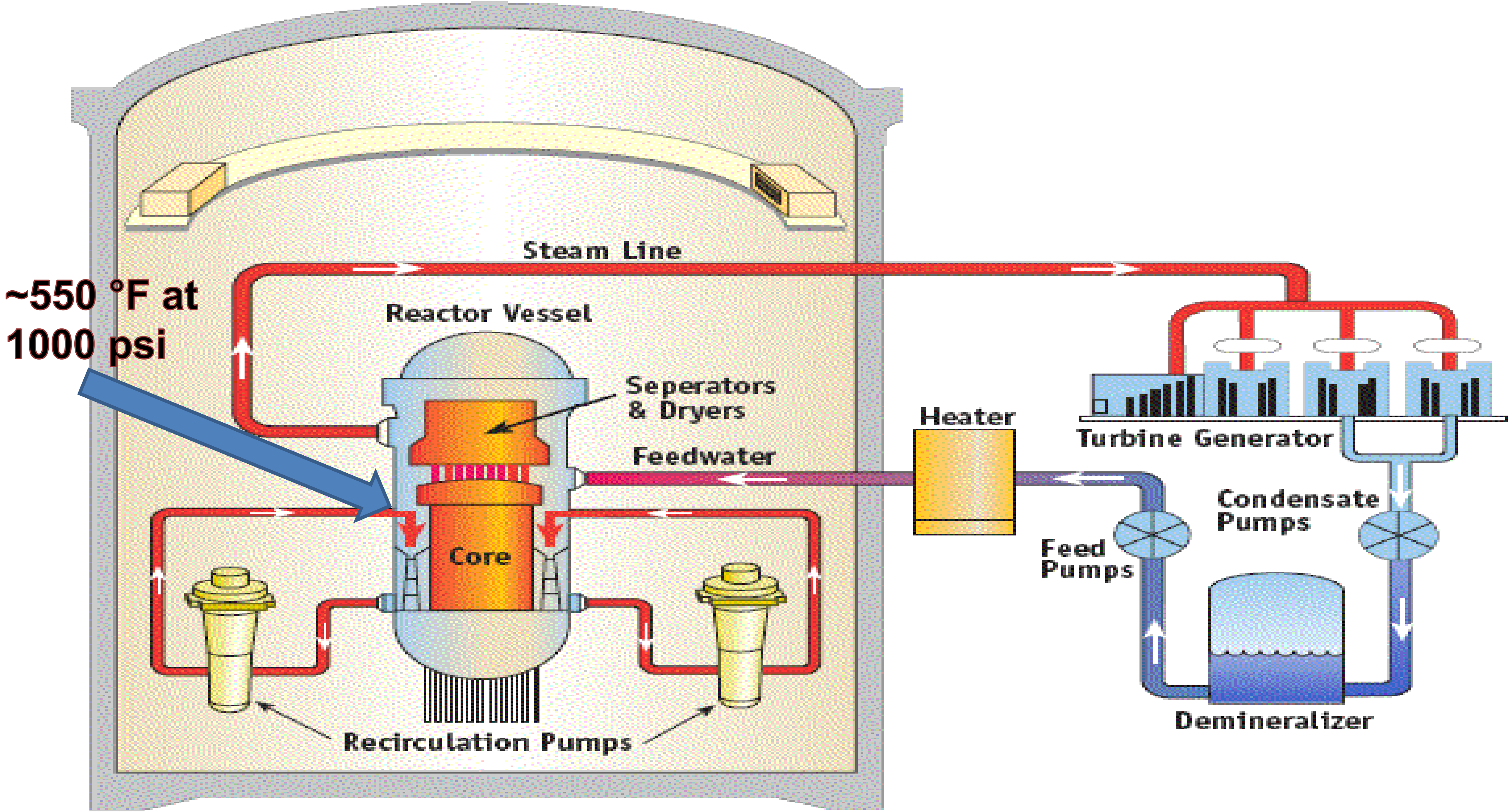

Pressurizer
Steam Generator
Secondary Loop
Turbine
Moisture Separator and Reheator
Generator
Circulating Pump
Coolant Pump
Reactor
Primary Loop
Condensate Pump
Tertiary Loop
Containment Wall
Nuclear Steam Supply System
MB 3618A

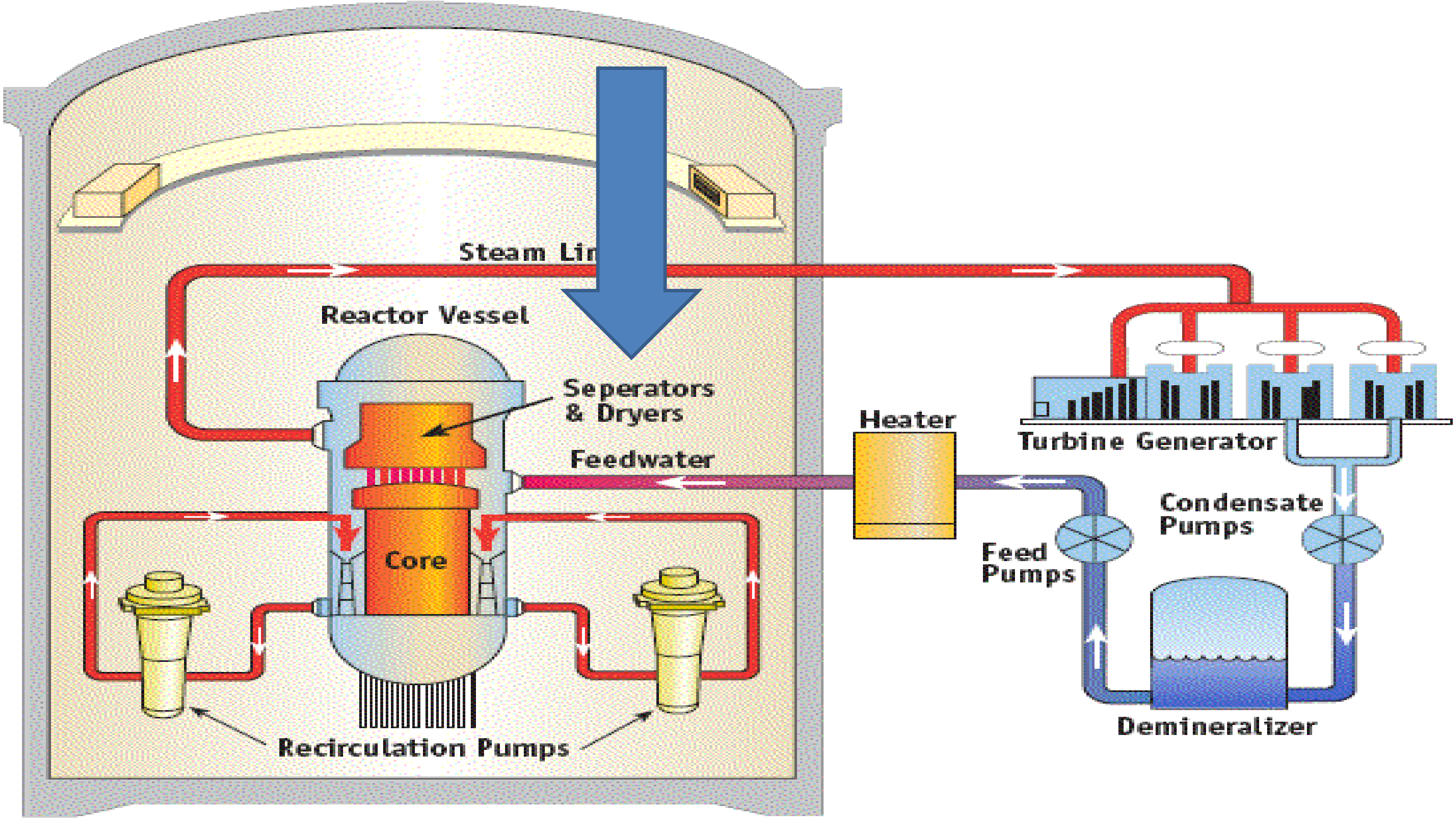
Pressurized Water Reactor



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

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


~550 °F at
1000 psi
Steam Line
Reactor Vessel
Seperators
& Dryers
Feedwater
Heater
Turbine Generator
Condensate
Pumps
Feed
Pumps
Core
Demineralizer
Recirculation Pumps


Steam Lin
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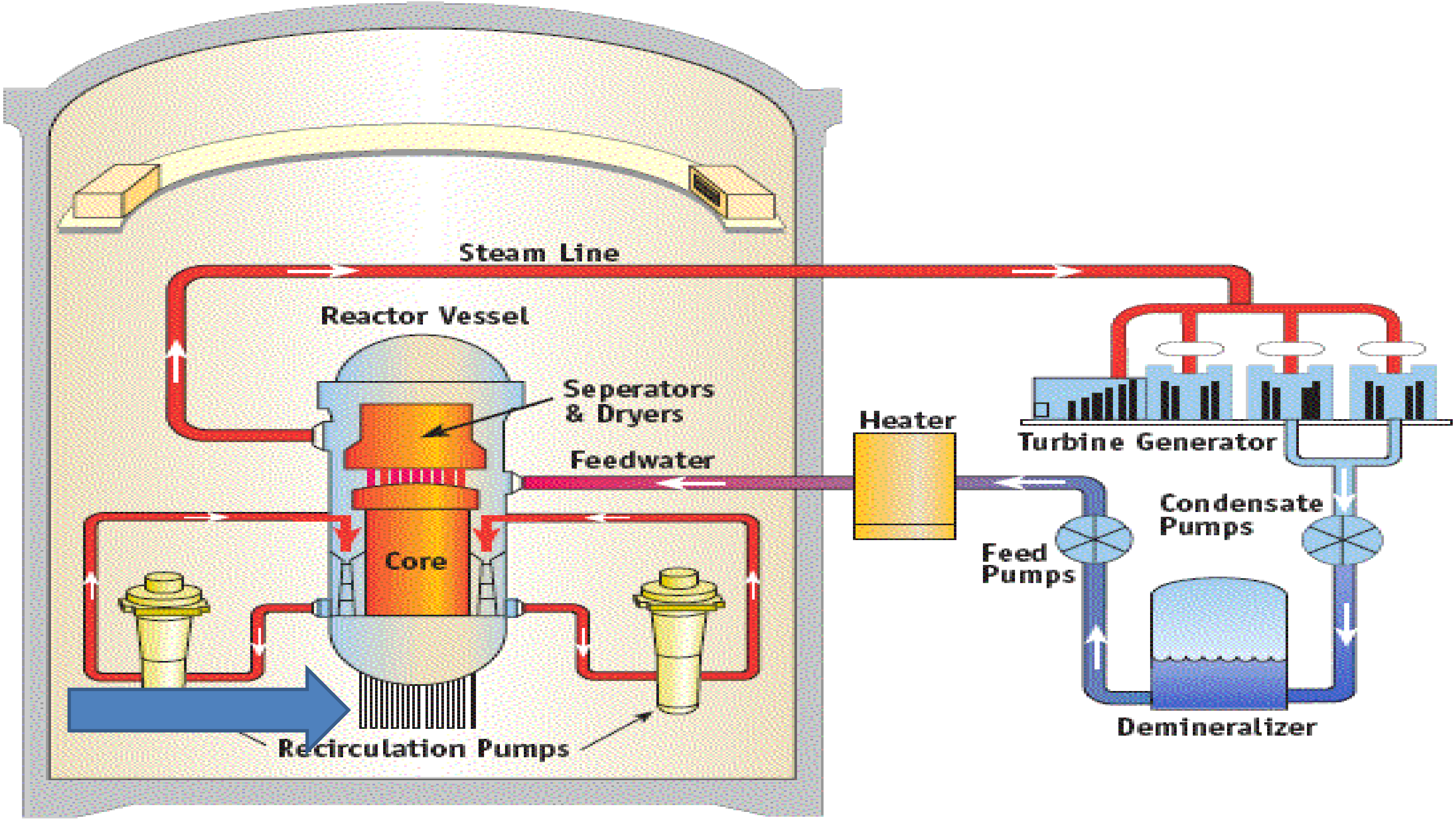
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Seperators
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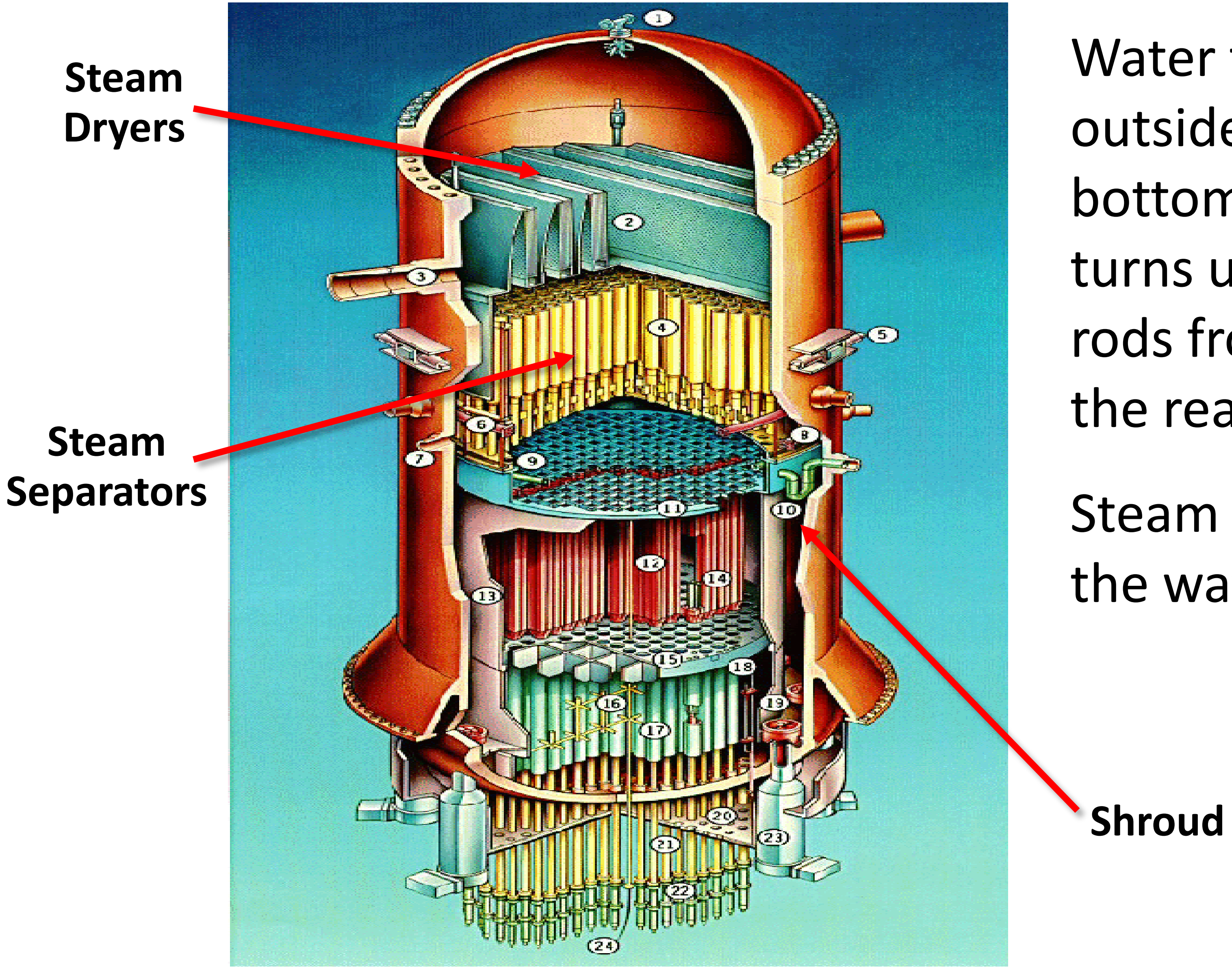
Heater
Turbine Generator
Condensate
Pumps
Feed
Pumps
Core
Demineralizer
Recirculation Pumps

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

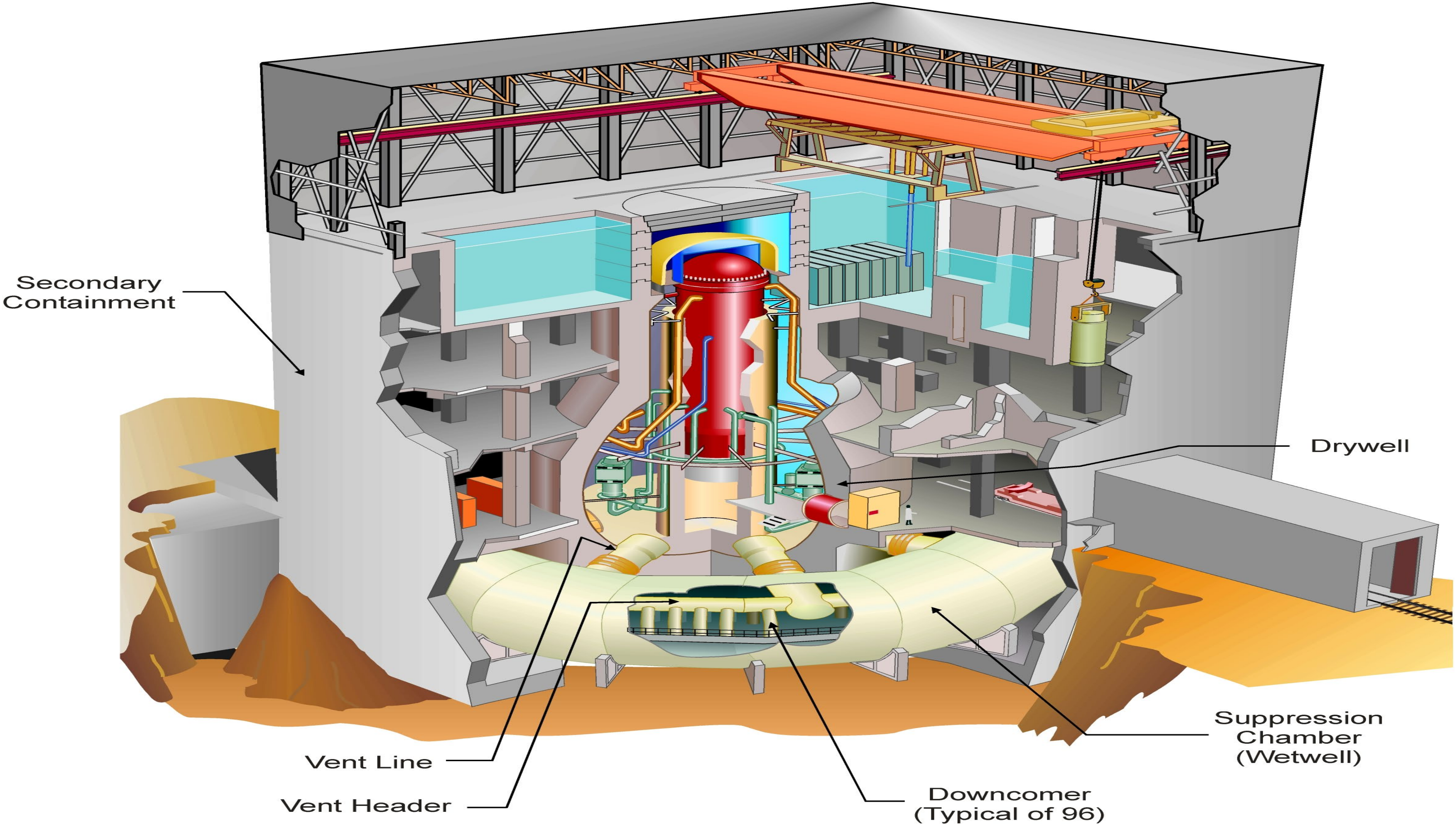
Standby Liquid Control

- 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
- Tank of highly concentrated boron solution adjacent to the reactor
- **<u>One-time event</u>**

BWR Components

Off-gas System

- Fission Gas by-products from the core that are carried over
  - Xenon, Iodine isotopes
  - Normal gasses present in the atmosphere 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
- 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.


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

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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

Start Time	End Time	Start MW	End MW	MWR	Duration	Comment
07/18/2024 15:25	07/18/2024 15:26	861	0	861	00:00:01	
07/18/2024 15:26	07/23/2024 01:21	0	0	861	04:09:55	Repair
07/23/2024 01:21	07/23/2024 02:21	0	37	824	00:01:00	Hold for Monitoring
07/23/2024 02:21	07/23/2024 04:21	37	262	599	00:02:00	Raise to 30%
07/23/2024 04:21	07/23/2024 06:21	262	262	599	00:02:00	30% NI Calibration
07/23/2024 06:21	07/23/2024 19:00	262	225	636	00:12:39	30% - 65% ramp, hold 30% due to turbine vibration issues
07/23/2024 19:00	07/23/2024 21:30	225	0	861	00:02:30	Remove Unit from Grid to perform balance shots
07/23/2024 21:30	07/24/2024 21:54	0	0	861	01:00:24	Turbine balance campaign
07/24/2024 21:54	07/24/2024 21:55	0	40	821	00:00:01	Sync to Grid
07/24/2024 21:55	07/24/2024 23:54	40	262	599	00:01:59	Raise to 30%
07/24/2024 23:54	07/25/2024 04:30	262	730	131	00:04:36	30% to 85%
07/25/2024 04:30	07/25/2024 06:00	730	730	131	00:01:30	85% NI Calibration
07/25/2024 06:00	07/25/2024 09:30	730	843	18	00:03:30	85% to 98% ramp
07/25/2024 09:30	07/25/2024 10:55	843	843	18	00:01:25	98% NI Calibration
07/25/2024 10:55	07/25/2024 11:55	843	861	0	00:01:00	98% to full load

Nuclear Limitations

- Baseload operation
- “Routine” maintenance typically performed online
- Some maintenance activities create a “1/2-SCRAM” Signal due to operating some systems in a compromised manner
- A grid event may cause the second half of the SCRAM signal and cause a unit trip

Nuclear Limitations

- Nuclear Regulatory Commission (NRC)
- **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

Generating Unit Principles of Operation

Hydro Conversion Process

Kinetic Energy (Falling water)

to

Mechanical Energy (Turbine)

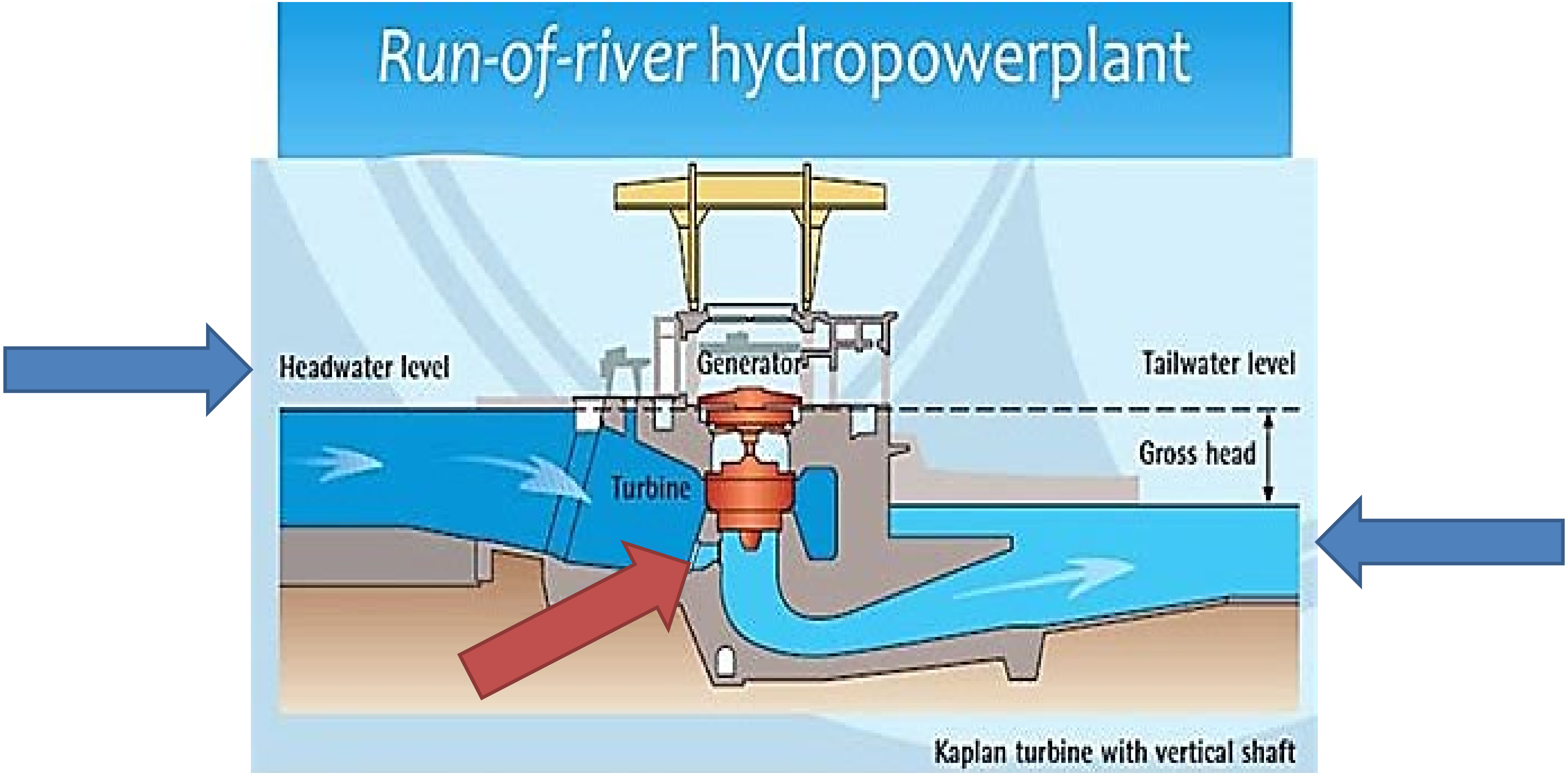
to

Electrical Energy (Generator)

Hydroelectric Generation

- Hydro once played a significant role in the electric utility industry accounting for 20% to 30% of the total energy produced
- Currently, hydroelectricity produces less than 10% of the electricity generated in America (about 1.0% in PJM)
- Renewable energy source
- Two types of hydroelectric generating plants:
  - Run of River
  - Pumped Storage

Hydroelectric Generation- Basic design elements



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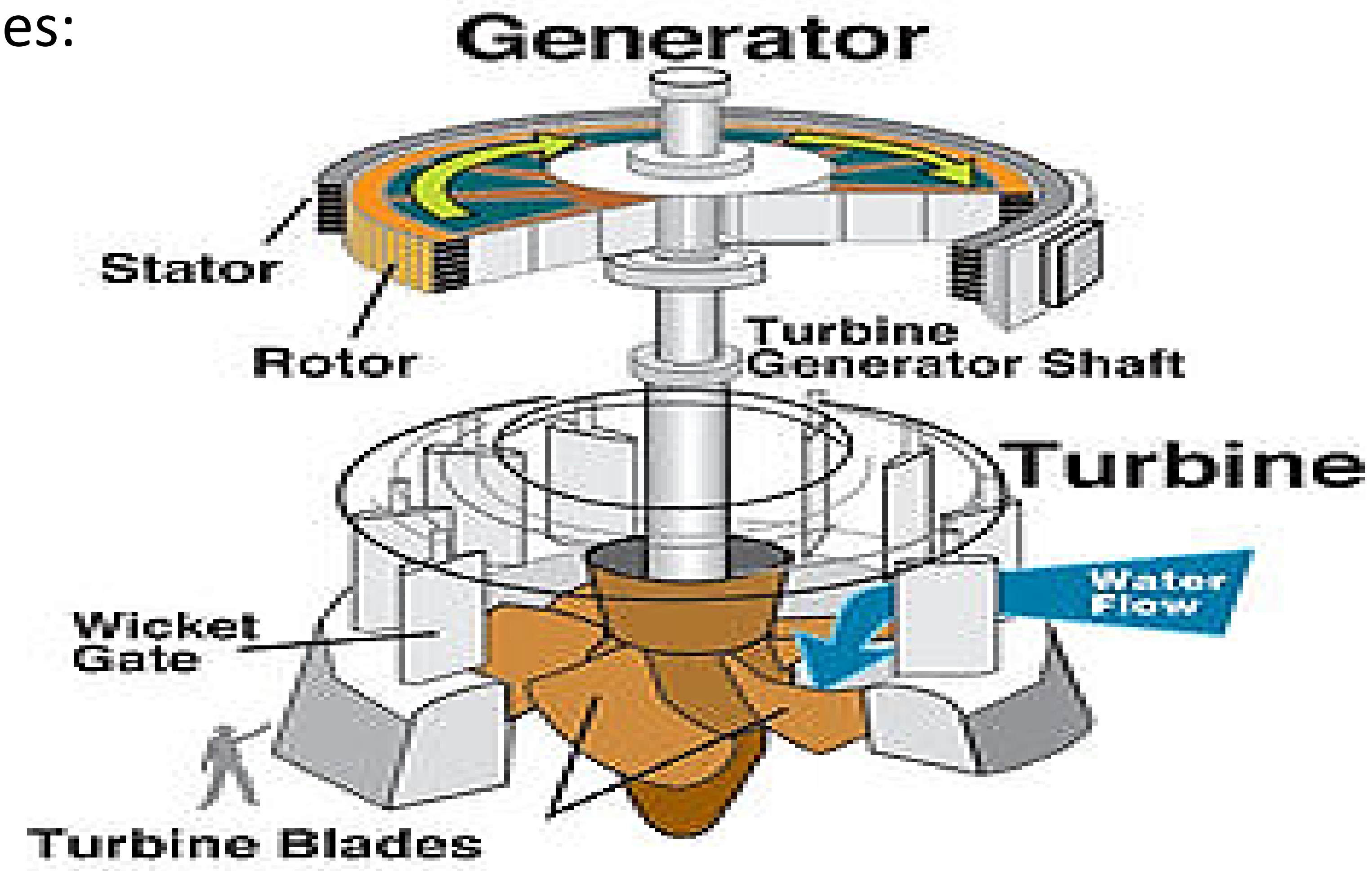
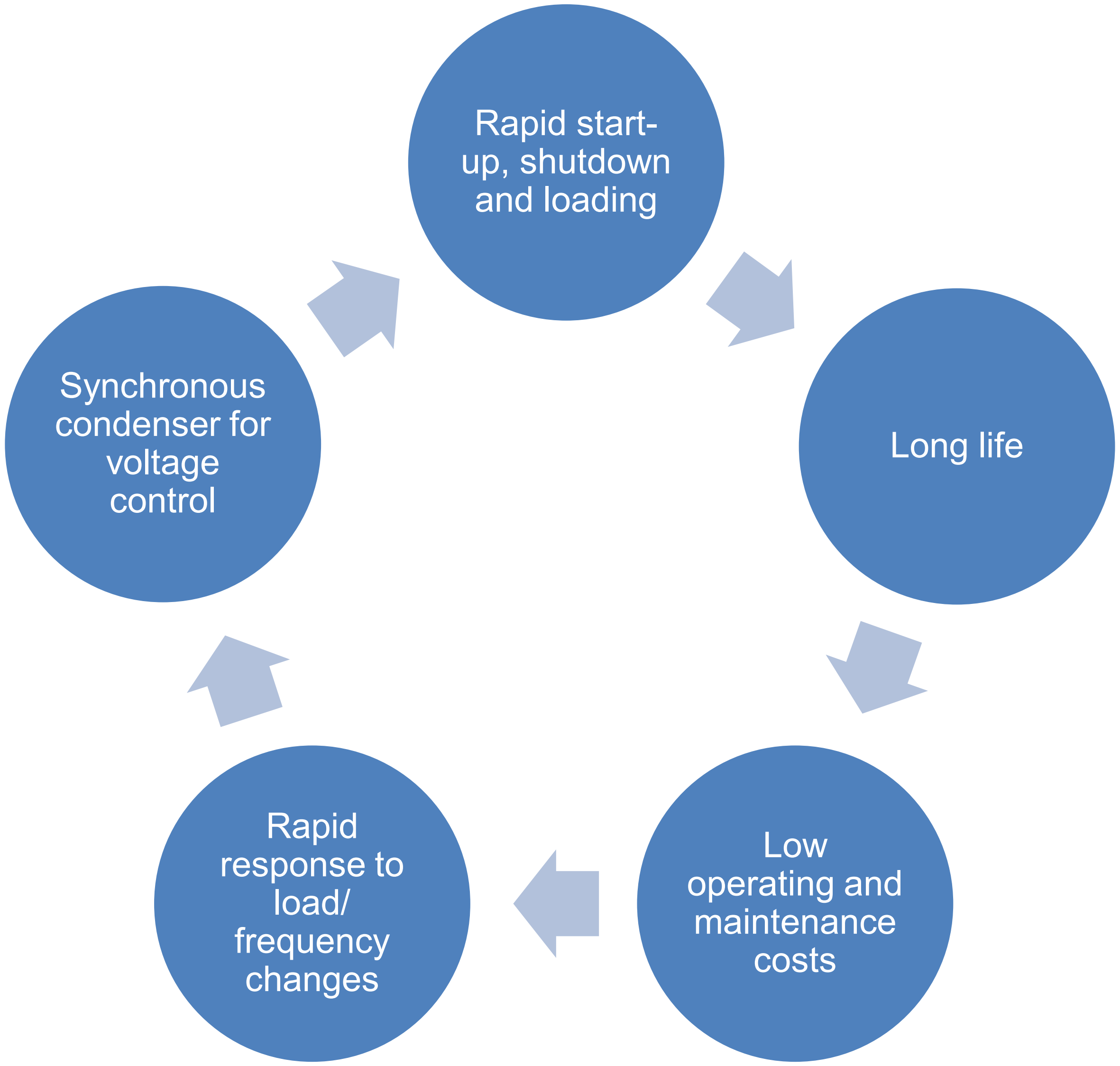
Hydroelectric Generation

- Power capacity of a hydro plant is the function of two variables:
  - Flow Rate of the water
  - Hydraulic head



Hydroelectric Generation

Both Run-Of-River and Pumped Storage units offer:



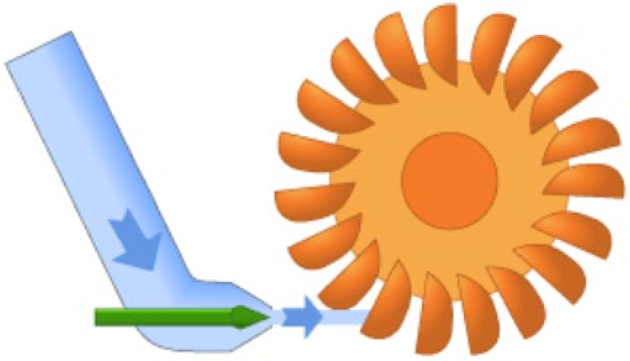
Types of Hydraulic Turbines

- **Impulse Turbine**
  - Used in high head, low flow plants
  - Low velocity head is converted 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:
  - Faster rotation 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

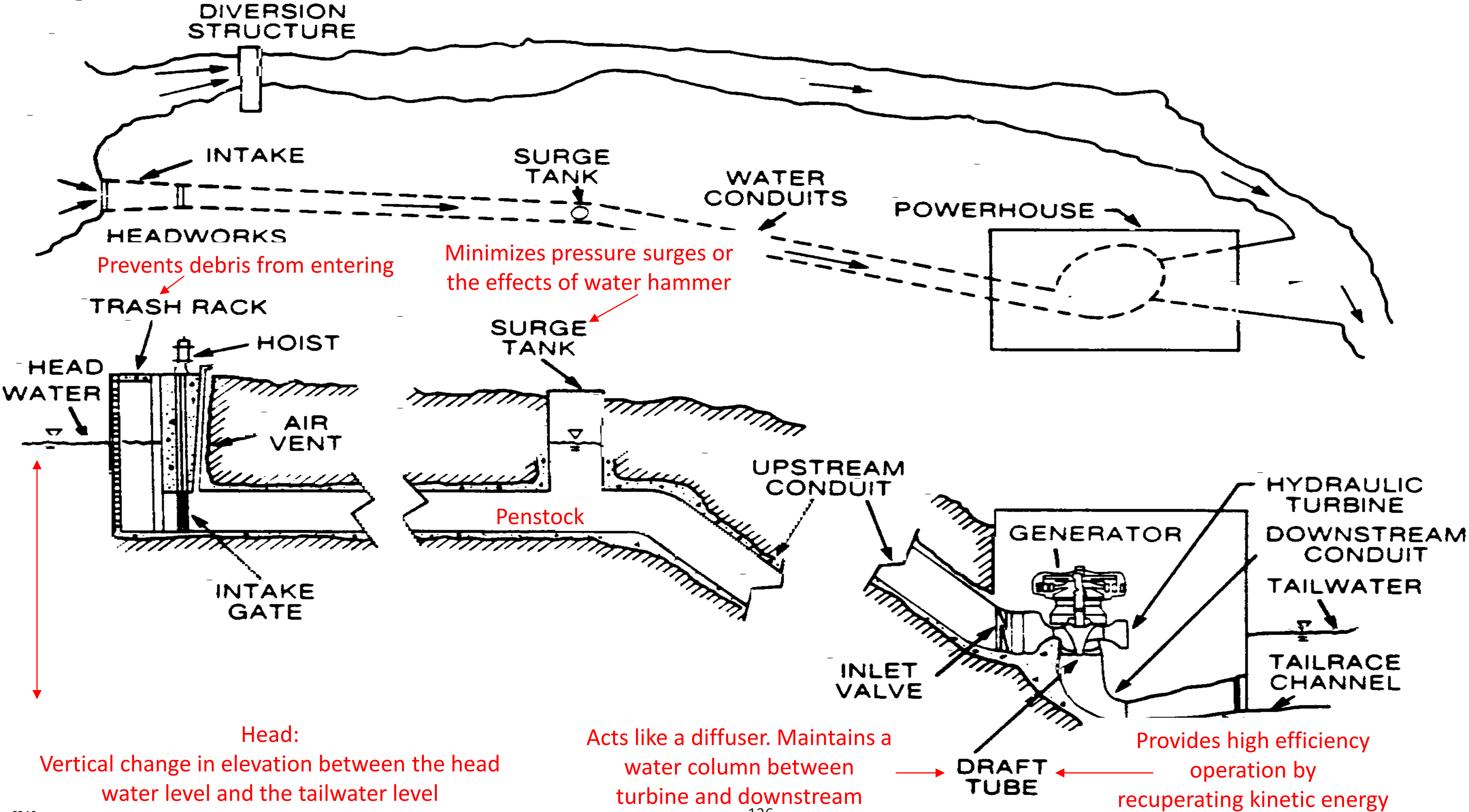
Run-of-River

Run-of-River

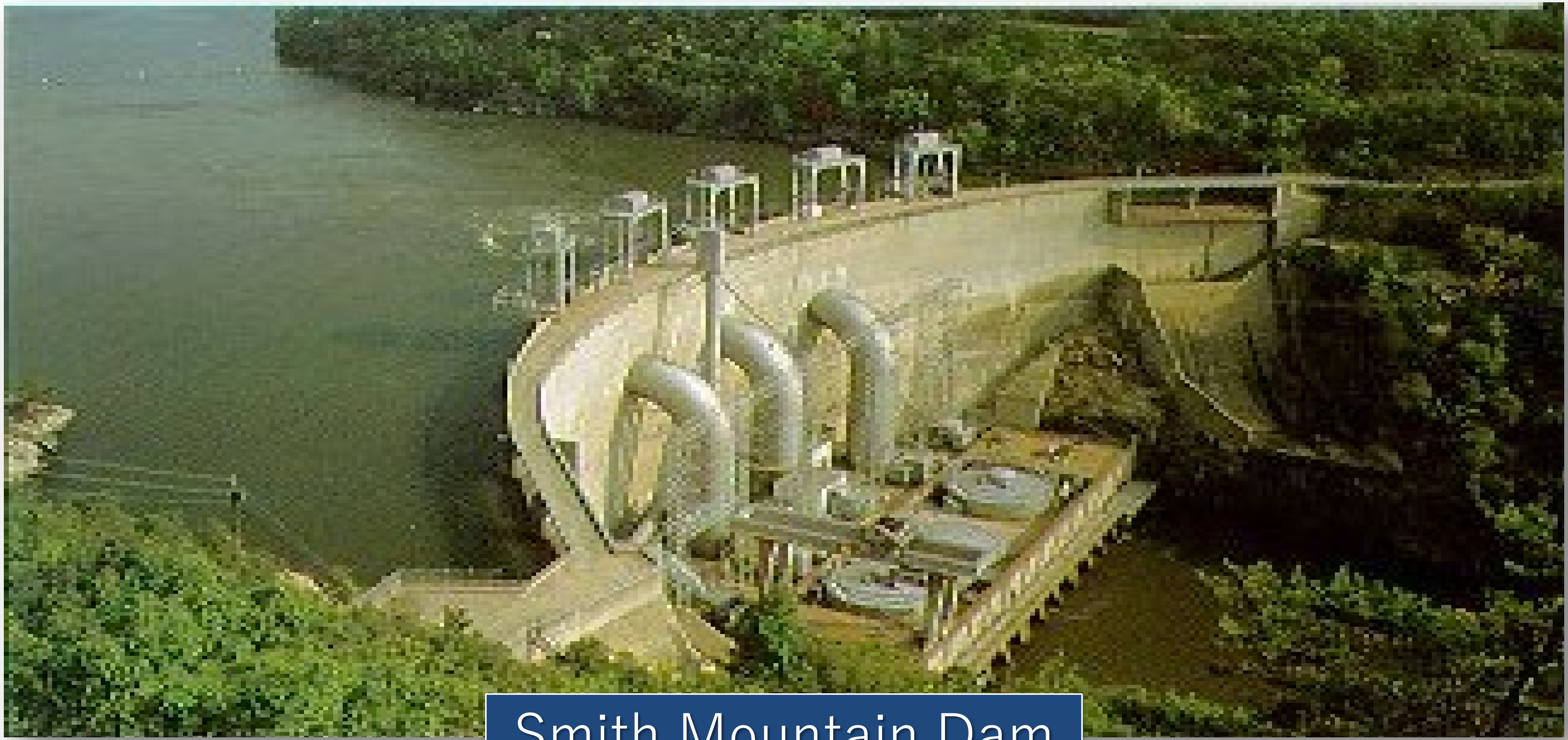
- Low impact method that utilizes the flow of water within the natural range of the river, requiring little or no impoundment
- Produce little change in the stream channel or stream flow
- Plants can be designed using large flow rates with low head or small flow rates with high head
- Advantages:
  - 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


DIVERSION STRUCTURE
INTAKE
SURGE TANK
WATER CONDUITS
POWERHOUSE
HEADWORKS
Prevents debris from entering
Minimizes pressure surges or the effects of water hammer
TRASH RACK
HOIST
SURGE TANK
HEAD WATER
AIR VENT
Penstock
UPSTREAM CONDUIT
HYDRAULIC TURBINE
GENERATOR
DOWNSTREAM CONDUIT
TAILWATER
INTAKE GATE
INLET VALVE
TAILRACE CHANNEL
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
DRAFT TUBE
Provides high efficiency operation by recuperating kinetic energy

Pumped Storage

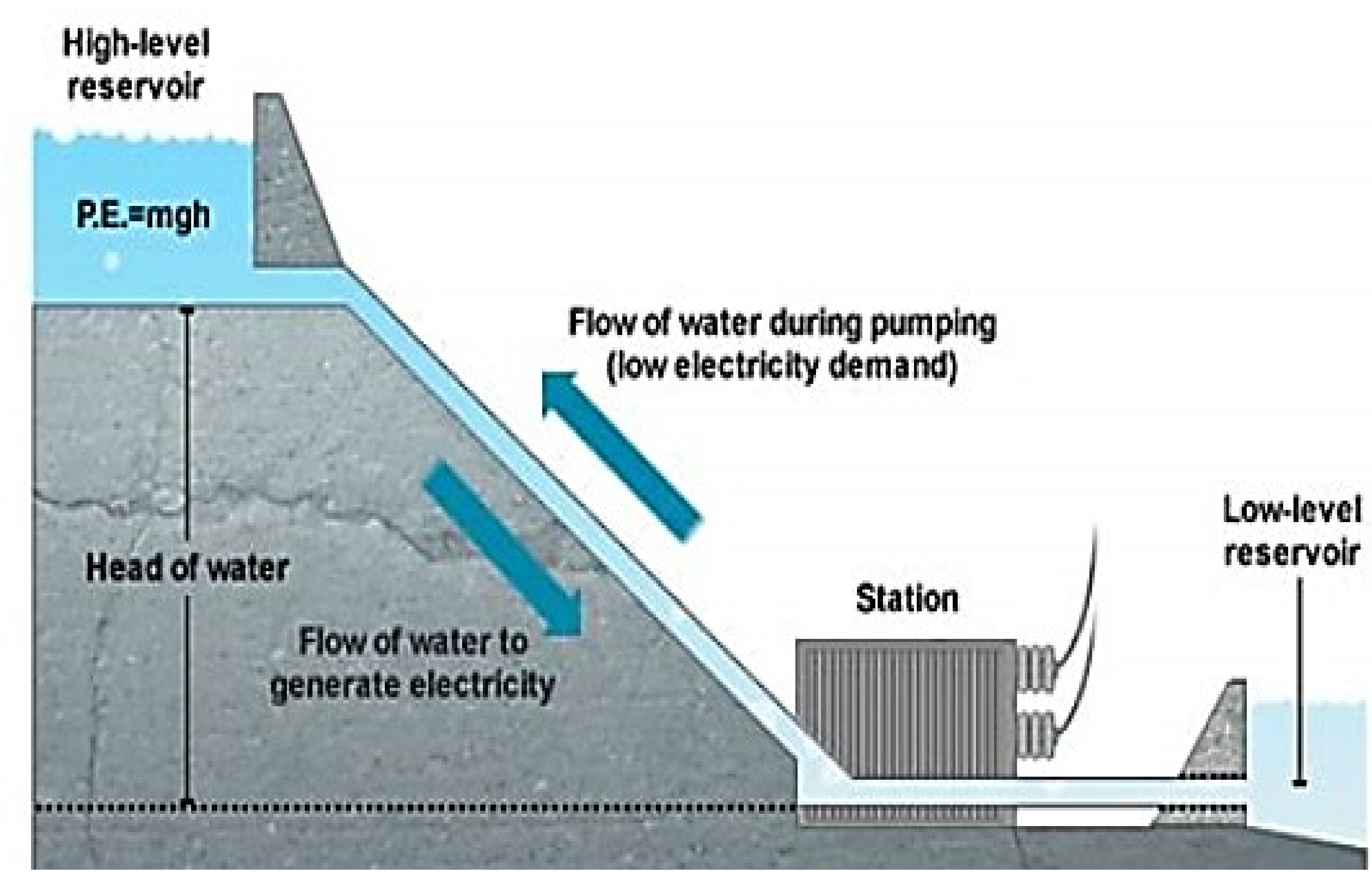


Smith Mountain Dam

Pumped Storage

- Off-peak pumping
- Peak period generating
- Reversible Francis-type turbine

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

Thermal Efficiency

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

Thermal Efficiency = BTU Content (Kwh)/Heat Rate (BTUs)

Combustion Turbines

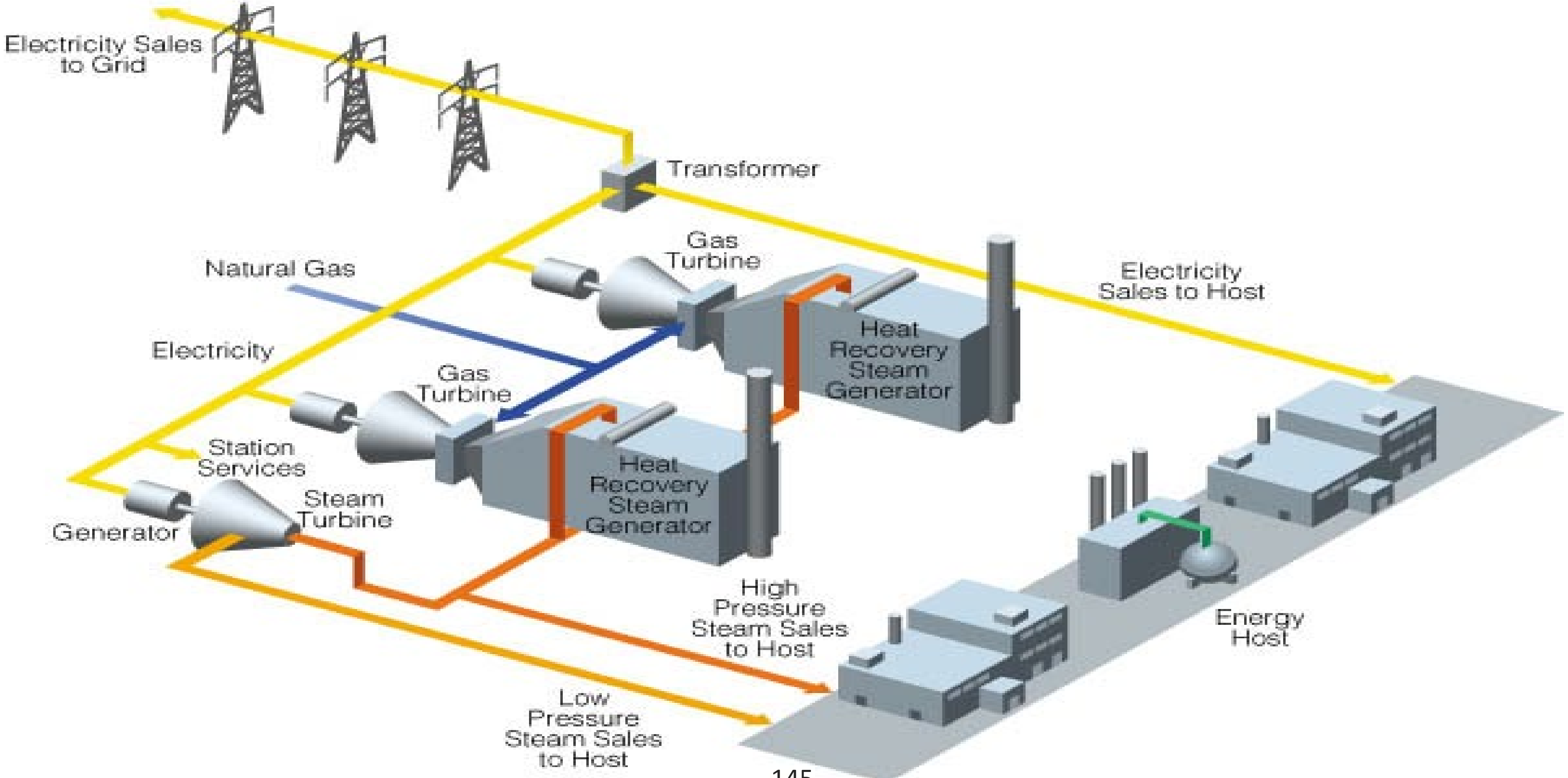
- Combustion turbines play an important role in utility system generation planning (36.6%).
- Combined-cycle units provide most of the advantages of simple-cycle peaking plants with the benefit of a good heat rate; they also requires less cooling water than conventional fossil and nuclear units of the same size.

Simple-Cycle Combustion Turbines

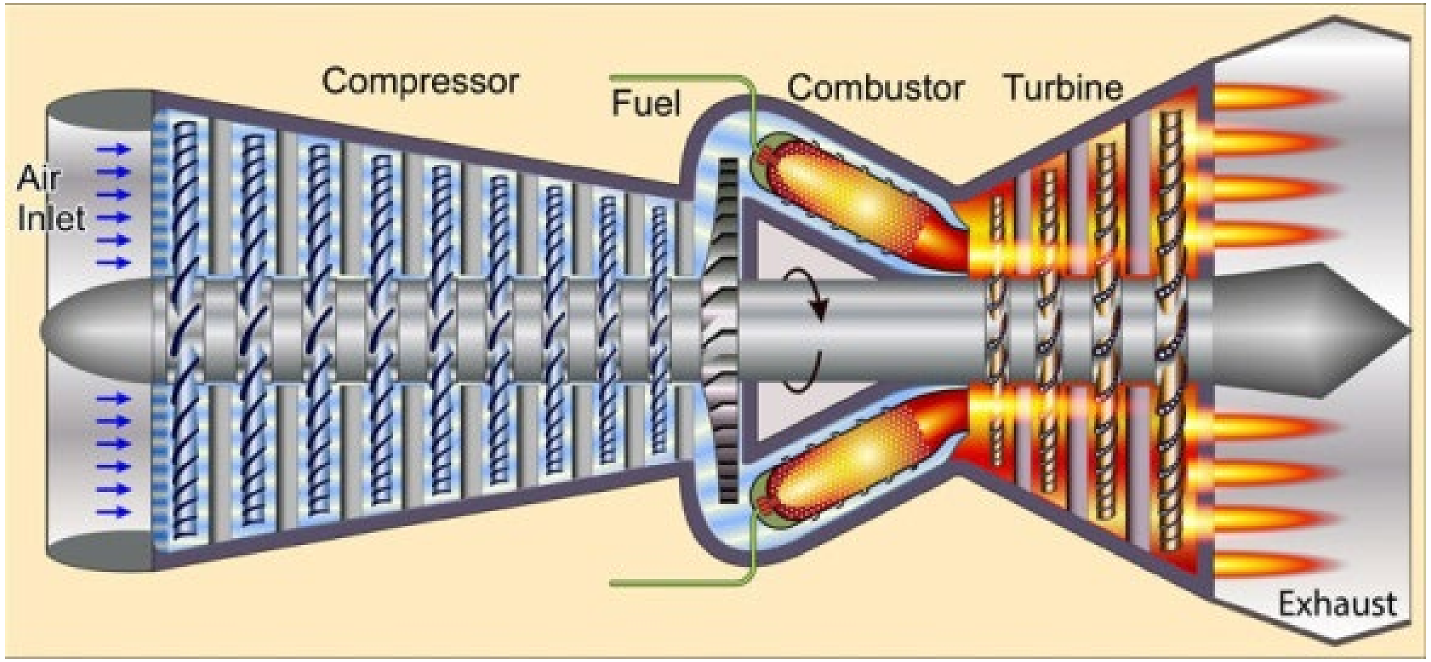
- Operation is similar to a jet engine
- Air is compressed, mixed with fuel in a combustor, to heat the compressed air
- The turbine extracts the power from the hot air flow
- 2/3 of the produced shaft power runs the compressor; 1/3 produces the electric power
- Typical capacity – 15-180 MW

Combined Cycle and Co-Generation

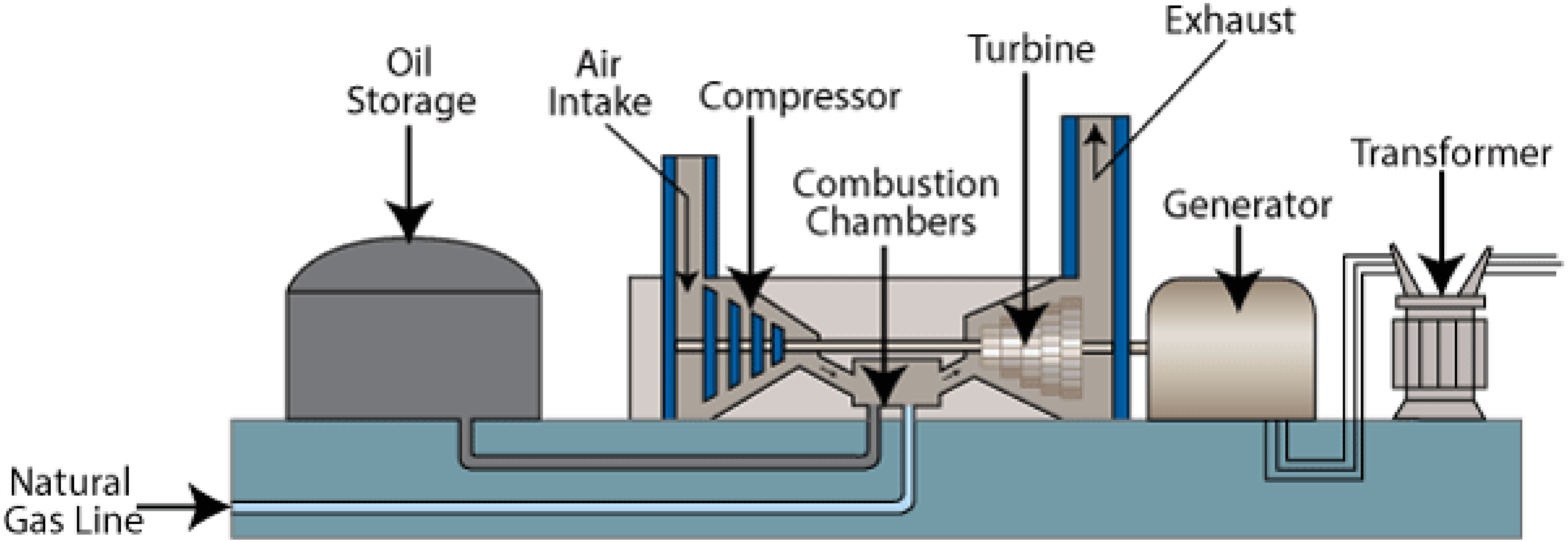
- Excess heat produced by a combustion turbine powers an additional turbine-generator



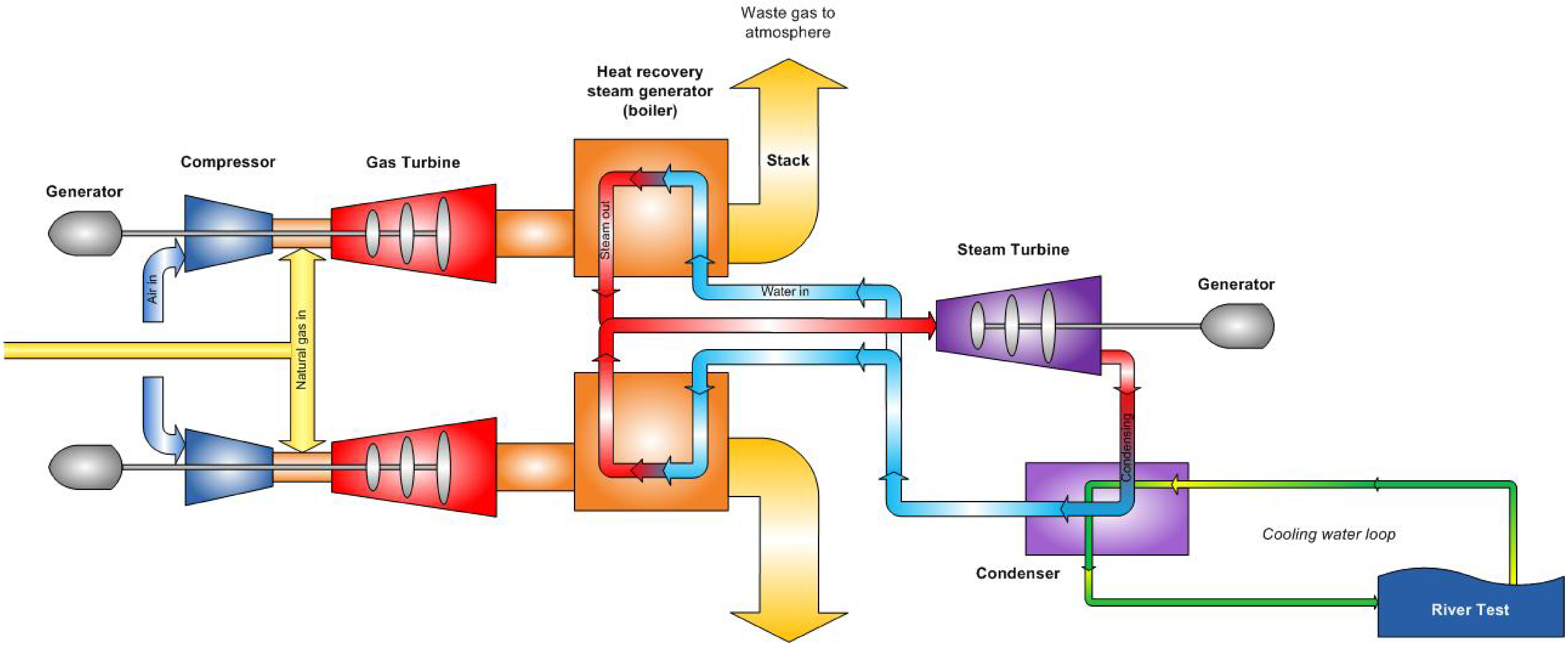
Combustion Turbine



Combustion Turbine



Combined Cycle Unit



Environment

- Gas Fired Combined Cycle Unit Advantages
  - Lower Emissions
    - SO_2 and Particulate emissions are negligible
    - NO emissions are lower than a conventional coal plant
    - No sludge or ash production/emissions
  - 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), 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

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

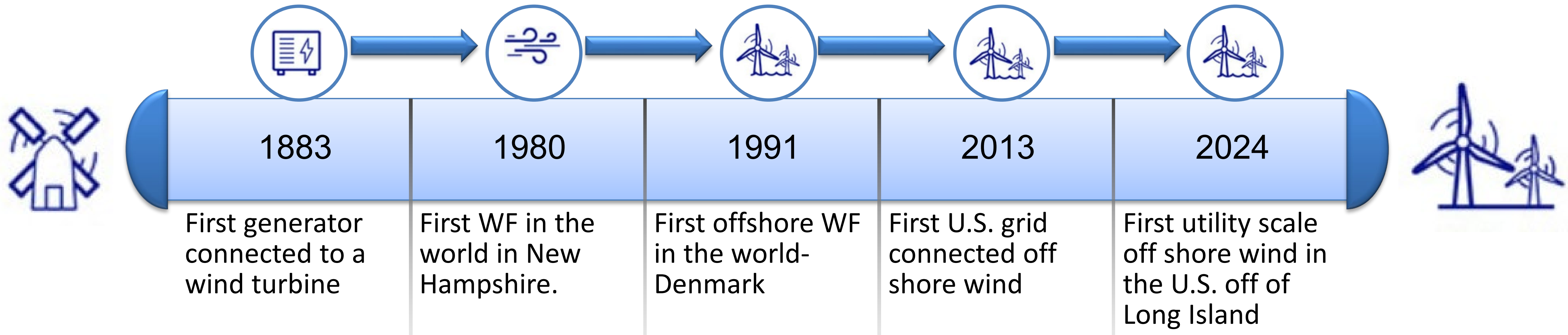
Combustion Turbines

- 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 (NO/CO_2/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

Wind Generation

Power System Elements

History of Wind Generation




Gansu Wind Farm,
China


Alta Wind
Energy Center

World's Use of Wind Generation

Country	Capacity (GW)	% Generation
World	1017	7.8%
China	442	9.4%
United States	148	10%
Germany	69	27.1%
India	45	4.2%
Spain	31	23.8%

Advancements in Technology

- Larger Blades
- Control system optimization

How does wind generation work?

Wind Conversion Process

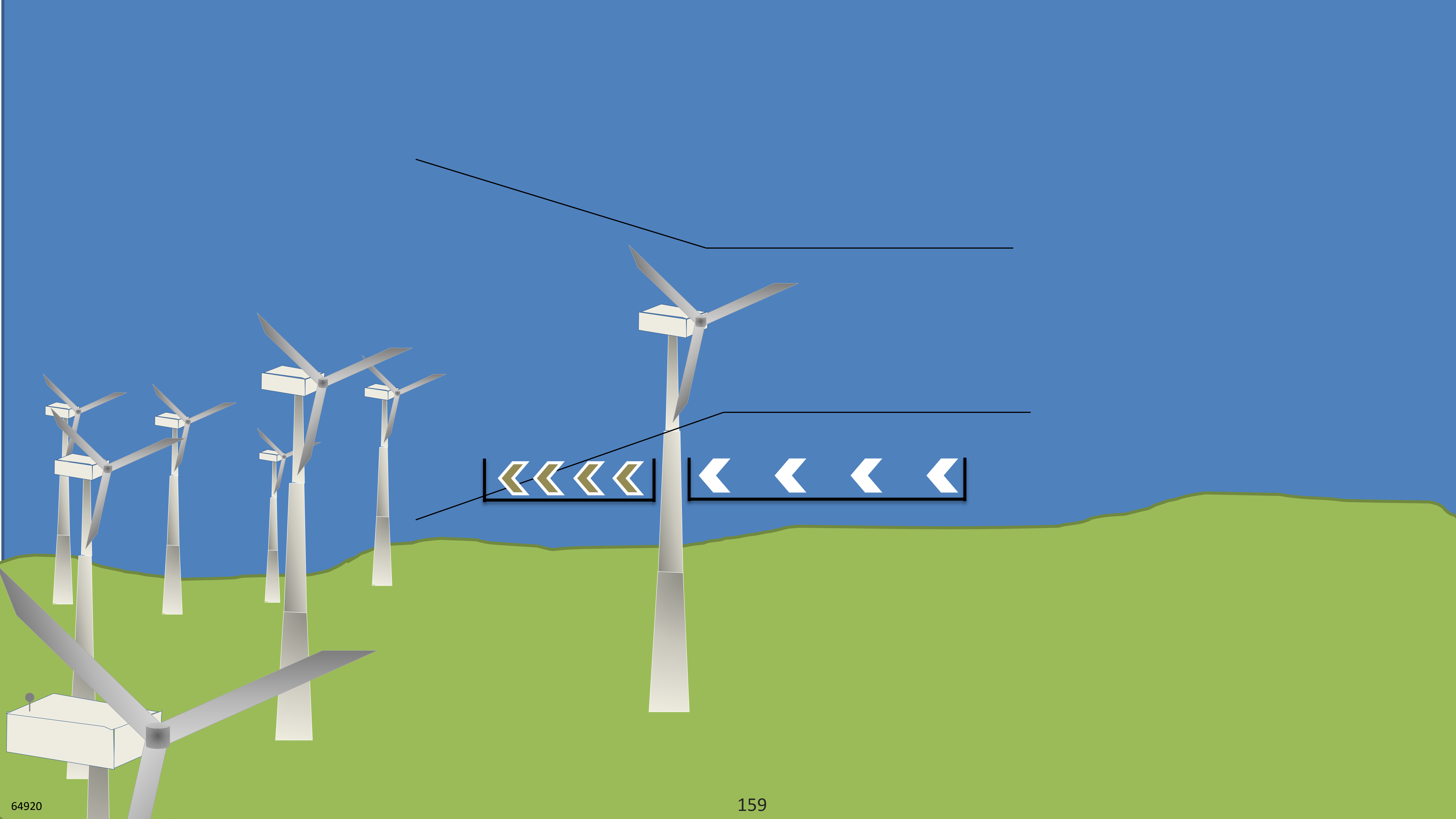
Kinetic Energy (Wind)

to

Mechanical Energy (Turbine)

to

Electrical Energy (Generator)



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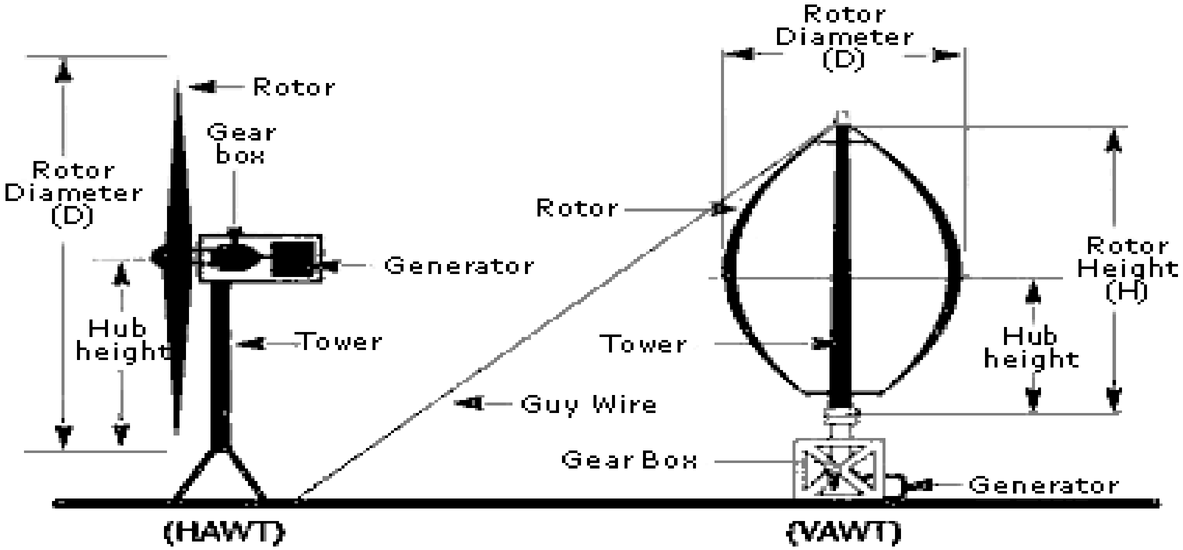
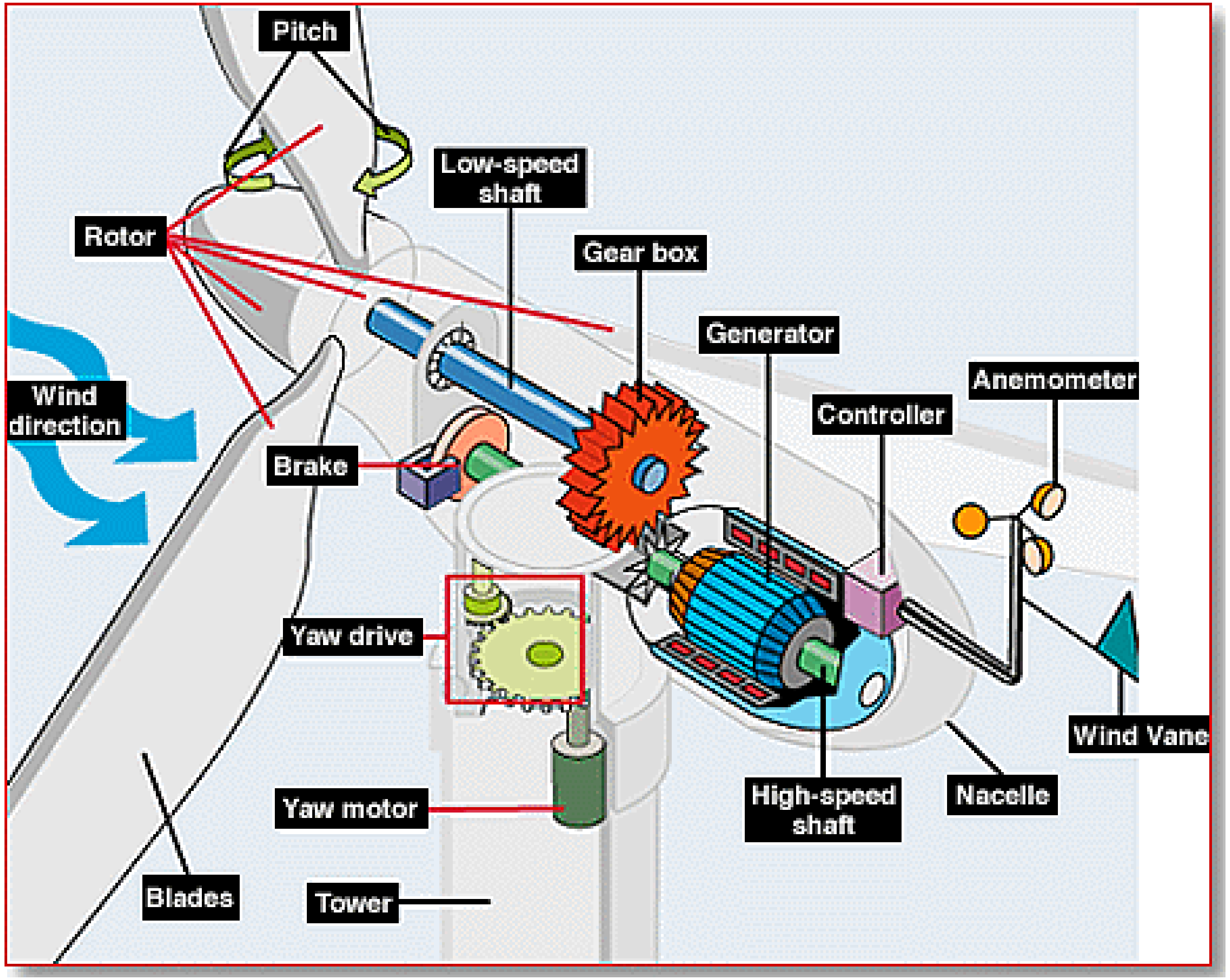
Wind Generation

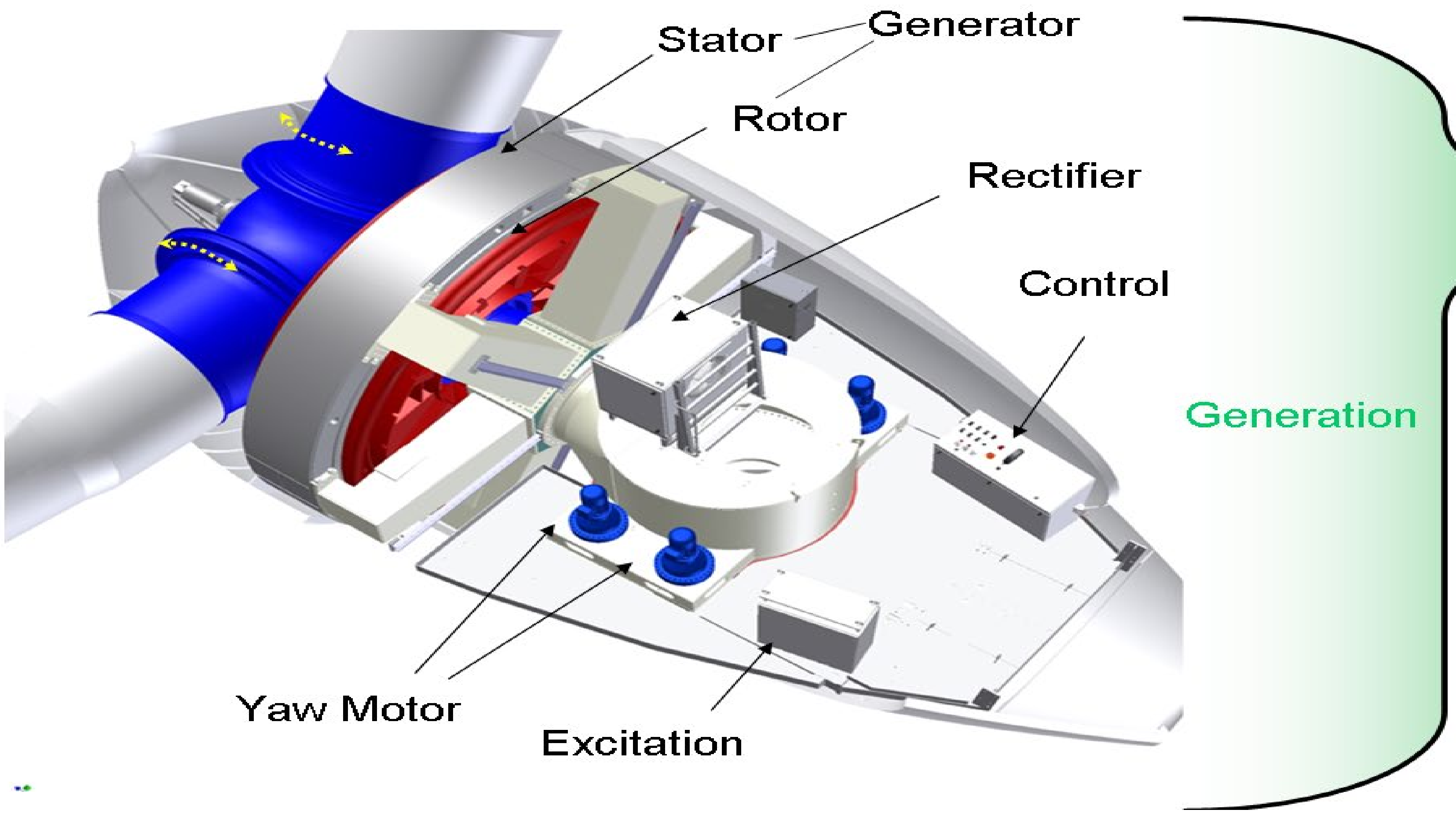
- Two basic types:
  - Horizontal axis turbines HAWT
  - Vertical axis turbines VAWT



Wind Power Generation



Wind Turbine Major Parts



Other type units may have gear boxes

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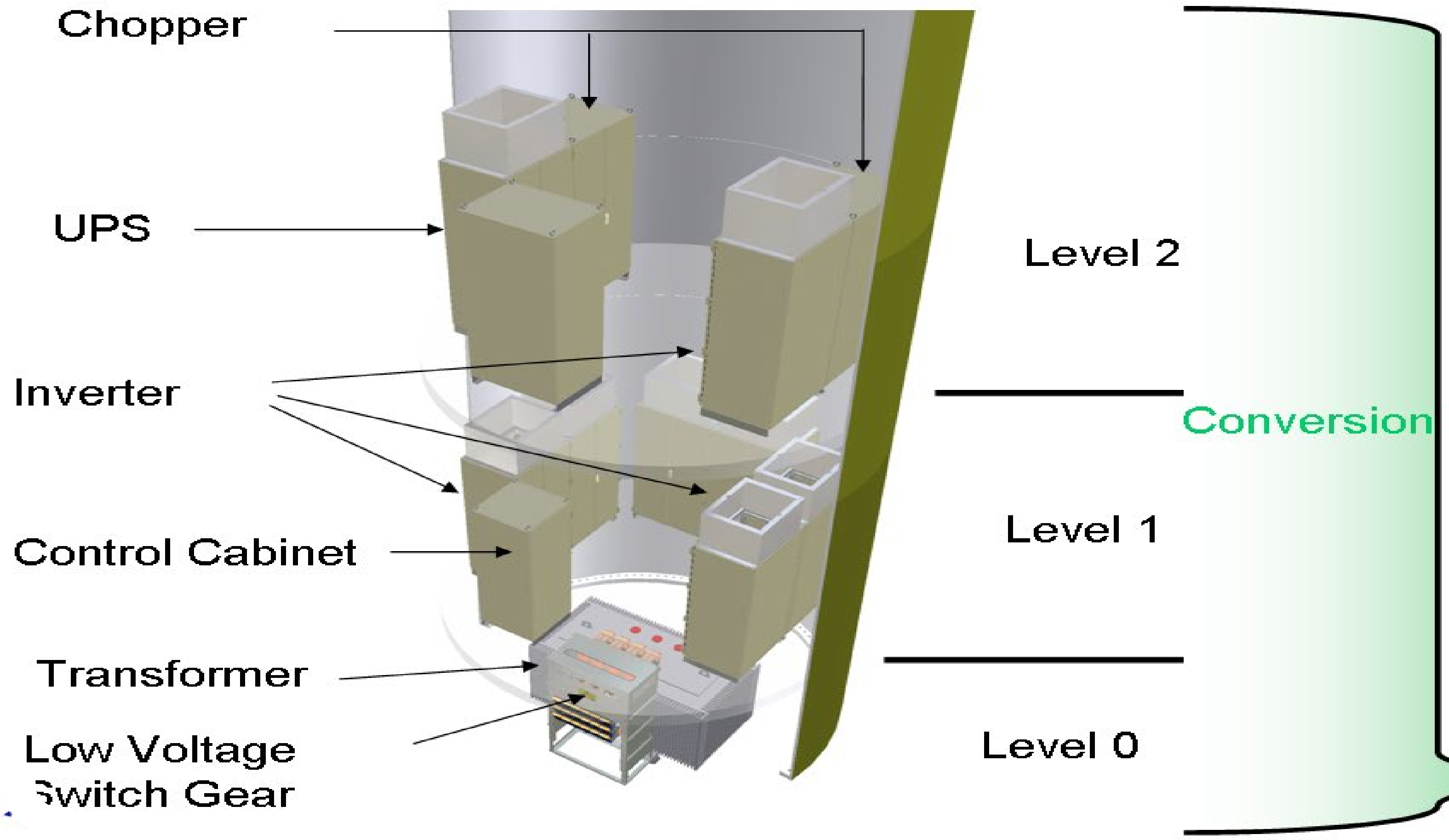
Tower Components



PJM Interconnection

New Entry Expectation by 2030

Resource Type	Nameplate (GW)		Installed Capacity (GW)	
	Low New Entry	High New Entry	Low New Entry	High New Entry
Natural Gas	3.8	8.8	3.8	8.8
Offshore Wind	10.0	10.3	2.6	4.1
Onshore Wind	14.3	43.3	1.0	6.7
Solar	23.9	40.4	4.6	6.1
Battery	3.4	3.6	2.8	3.2

Solar Generation

Power System Elements

History of Solar Generation

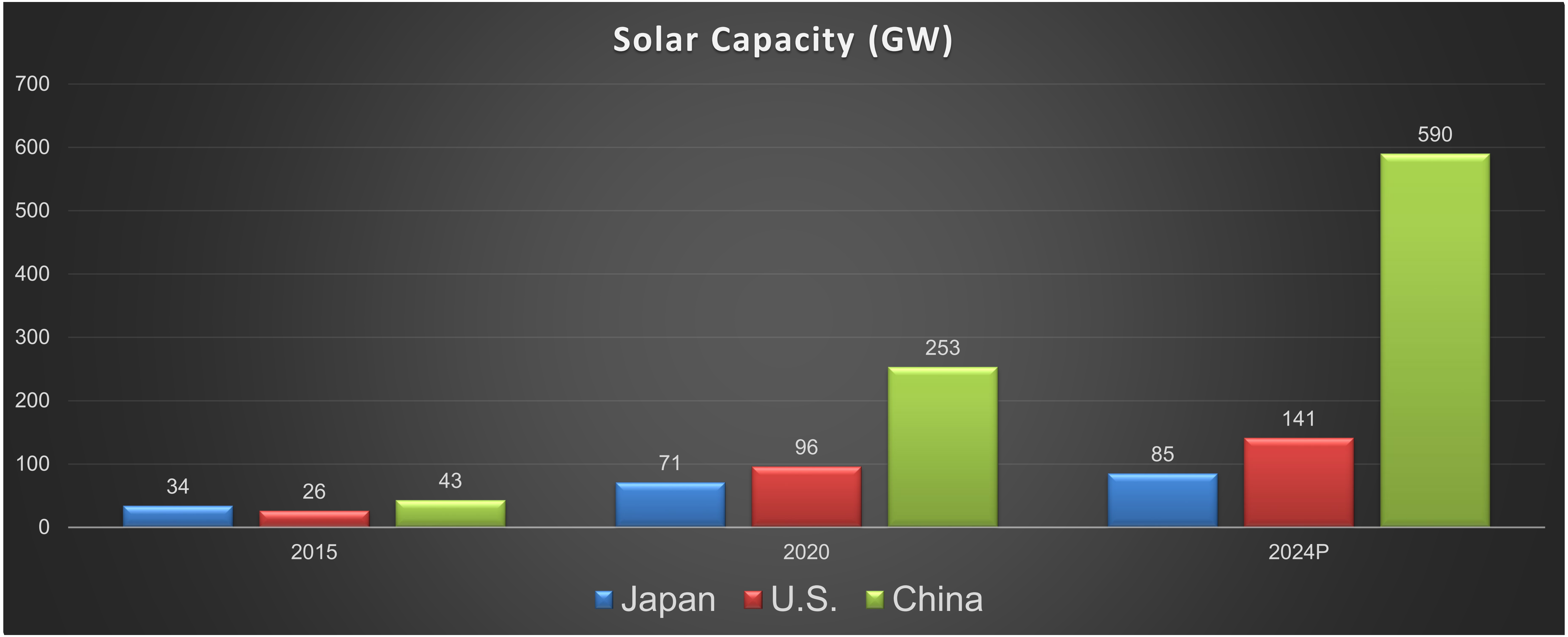
Modern Solar Cell (1953)
- First silicon PV Cell

Finding Applications (1950s & 1960s)
- Radios and Toys
- Satellites

Solar Spread (1970s & 1980s)
- The Coast Guard
- Railroads & Telecom
- Electrification Revolution
- Rooftop Solar

Modern Age (1990s & 2000s)
- Cheaper solar cells
- Making everything green

History of Solar Generation



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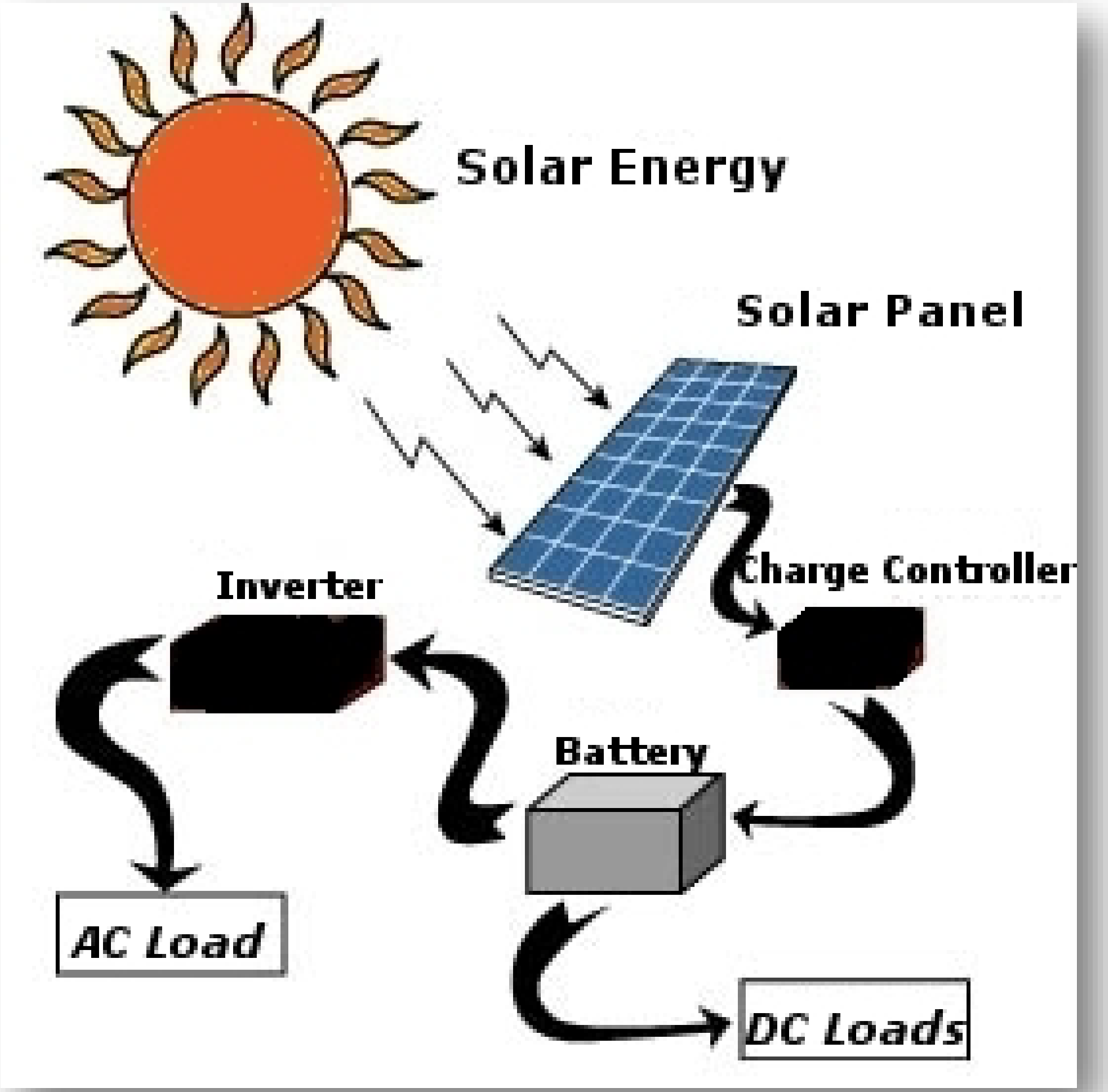
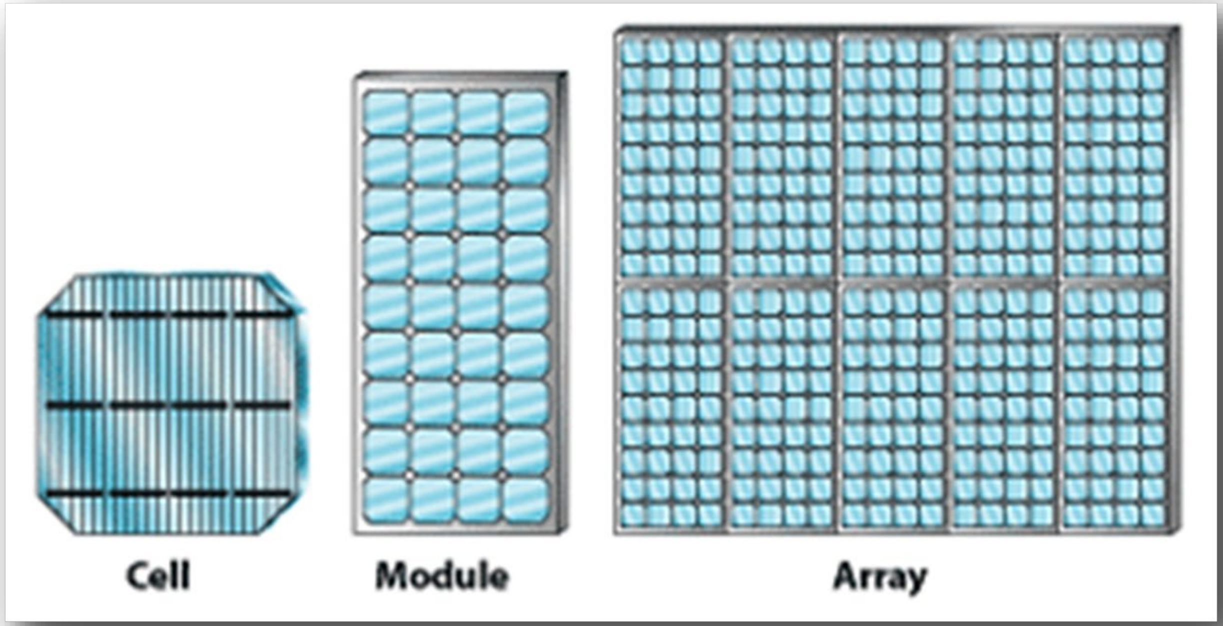
Solar Generation





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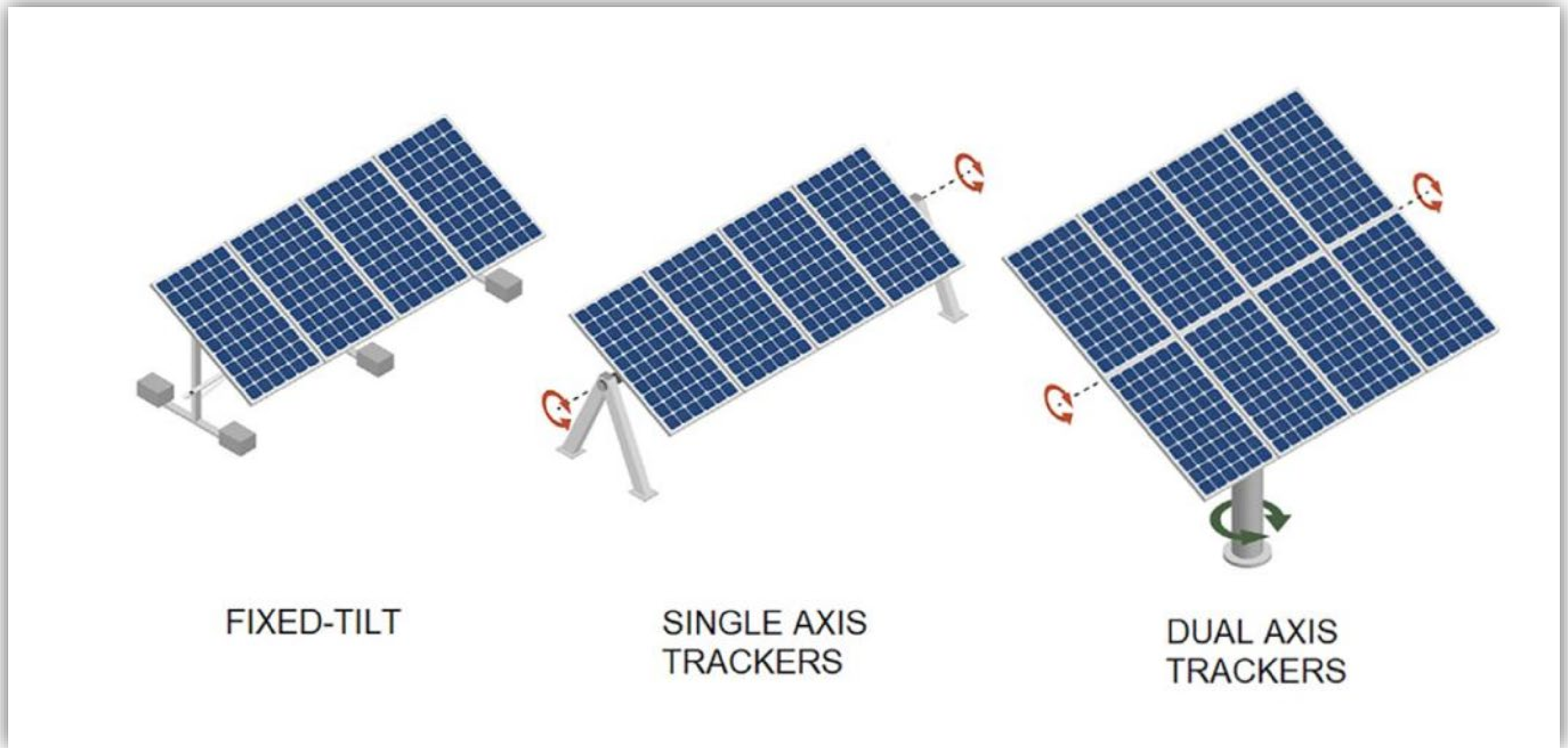
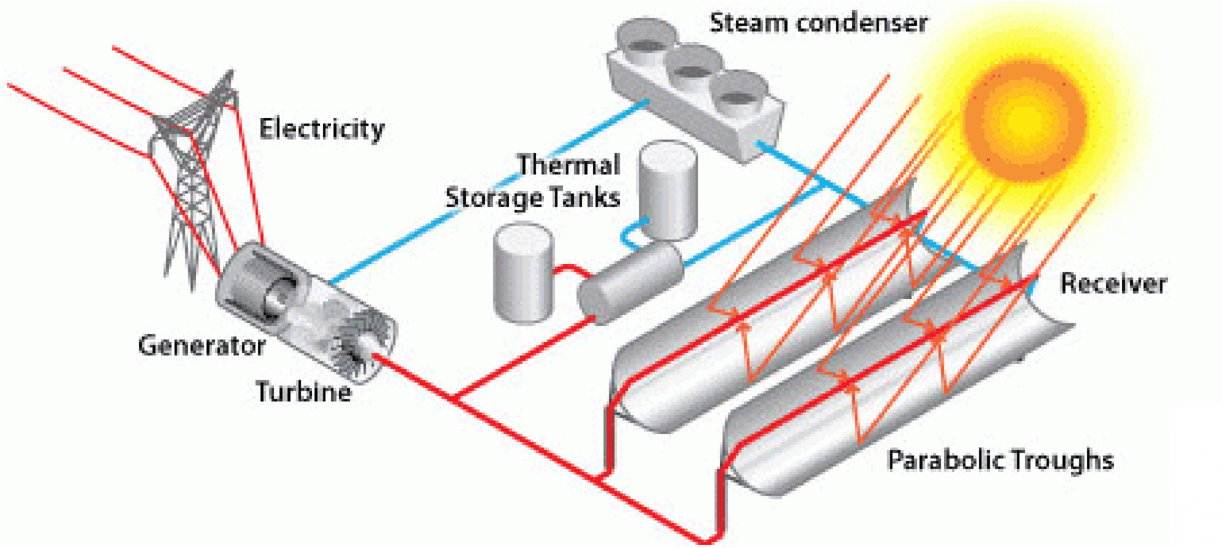
Fixed vs Tracking

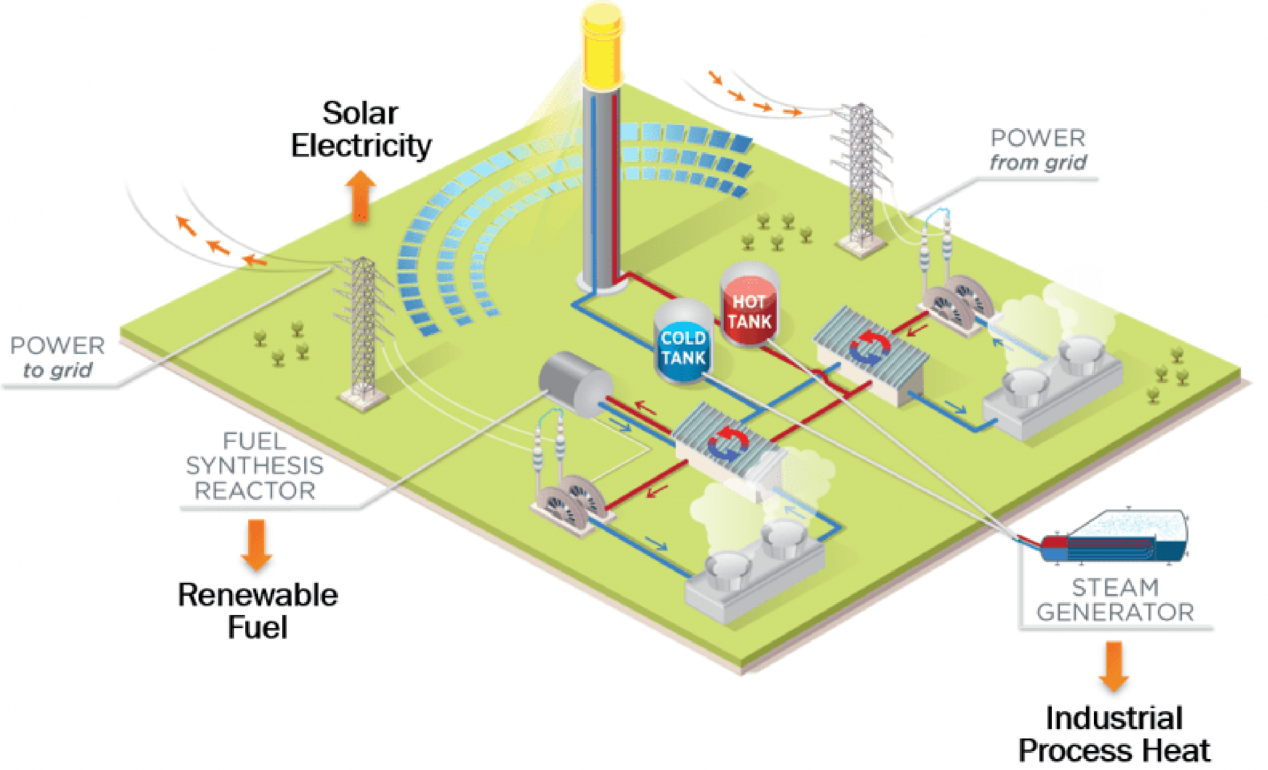


Concentrated Solar-Thermal (CSP)



Linear

Pole Tower



Thermal Storage System

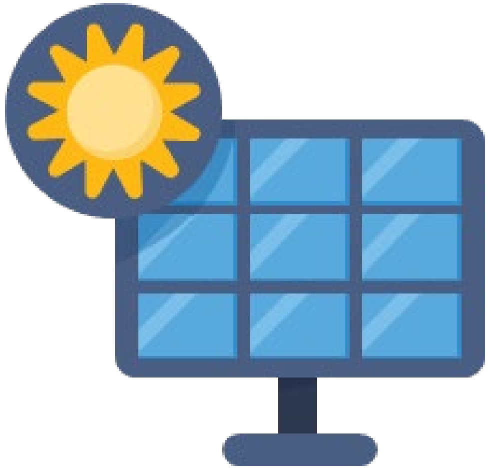
2022:
27,000 MW

→

2030:
354,000 MW

Reactive Capabilities

Fault Ride Through



Supply VARs

Absorb VARs

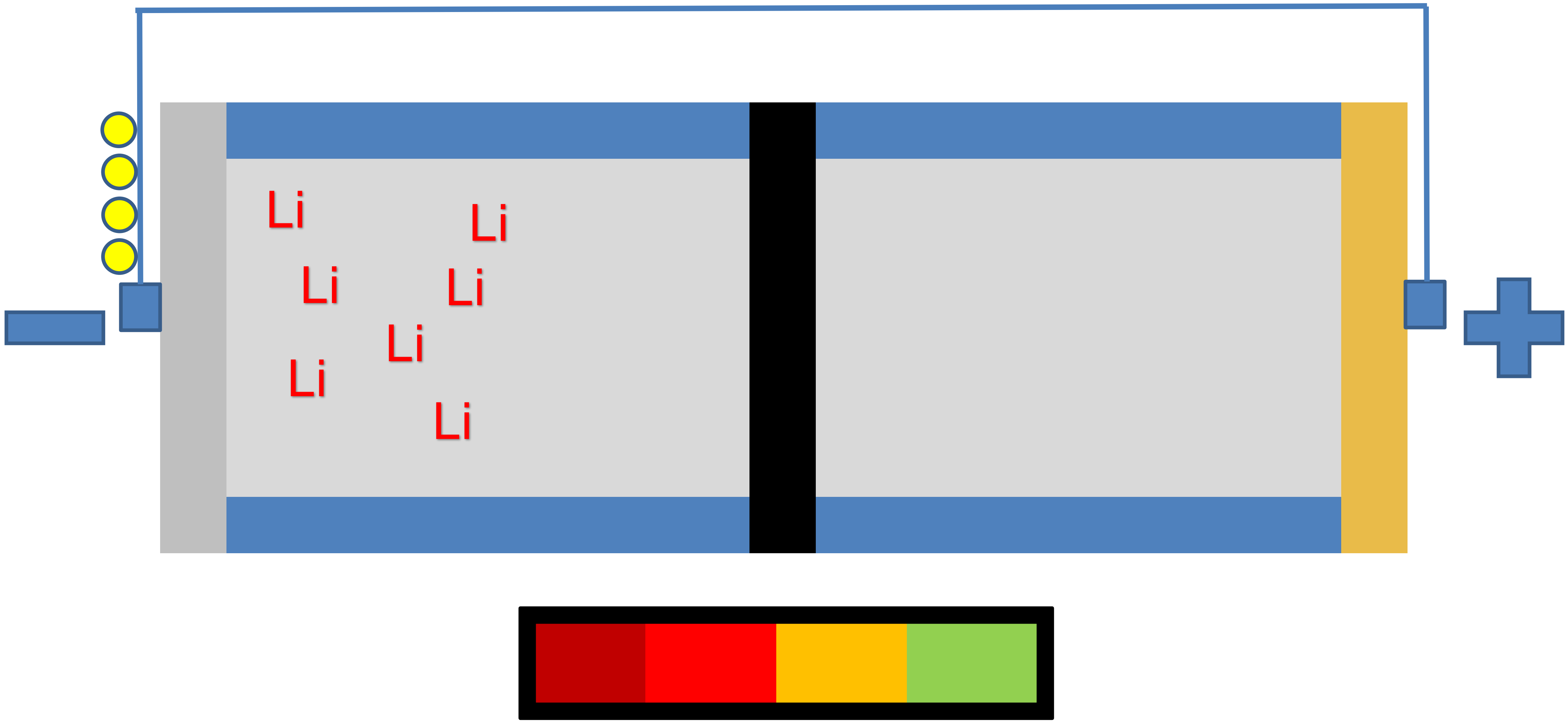
Battery Energy Storage

Power System Elements

History of Battery Energy Storage

Battery racks provided by LG Energy Solution sit in former turbine halls at Moss Landing Energy Storage Facility, California. Image: LG Energy Solution

How does it work?



Battery Use

pjm

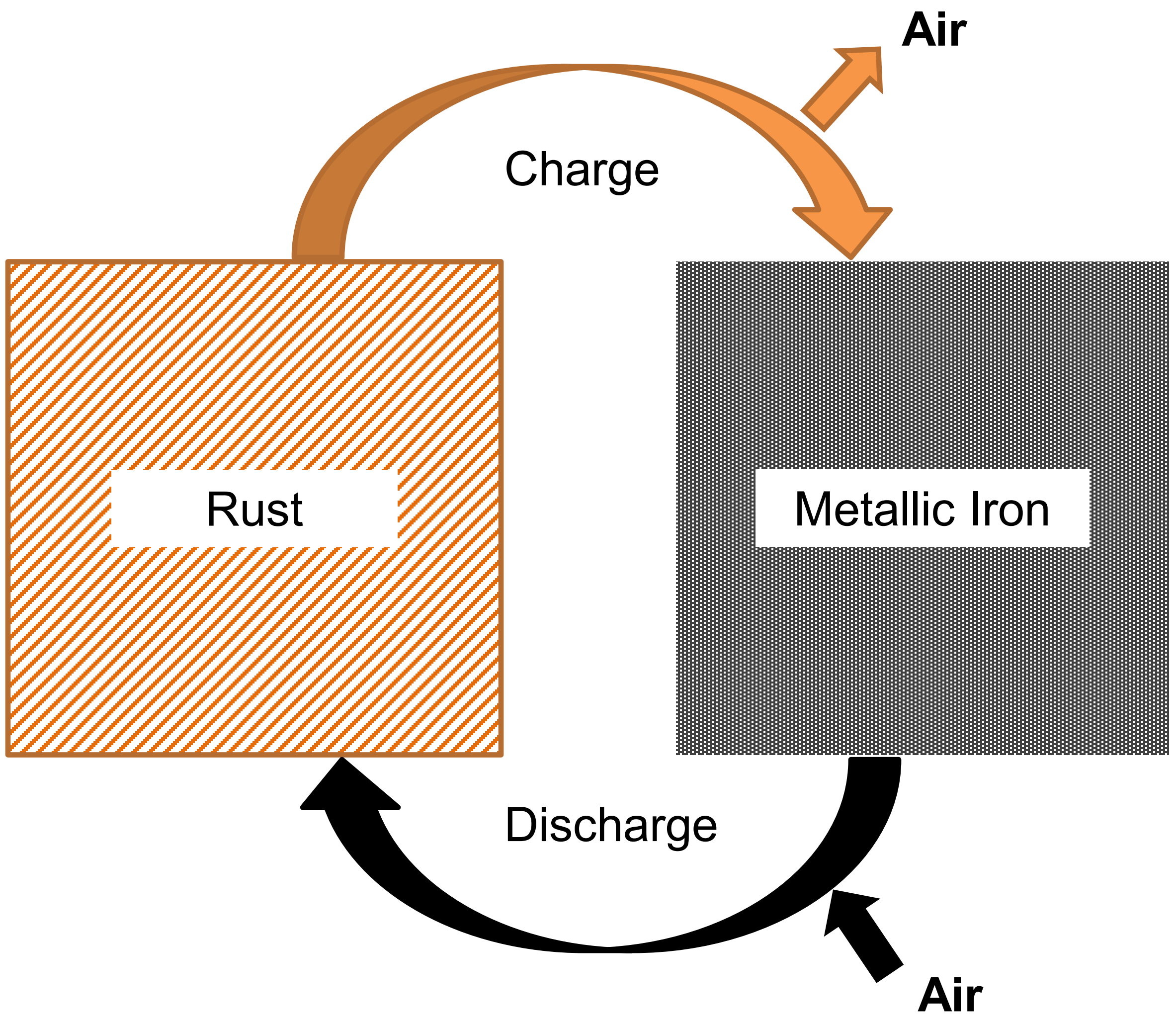
- Regulation Market

California ISO

- Arbitrage
- Frequency Control
- ACE Regulation

Different Designs

- Lithium Ion
- Zinc Air
- Iron Air
- Magnesium Ion
- Sodium Ion
- Lithium Sulphur



Battery Roadblocks/Hurdles

- Raw Materials
- Durability
- Storage Duration

Major Advancements/Future

- Cell design and chemistry- higher energy density- longer lasting, charge speed
- Solid State Batteries
- Next Gen Lithium Ion: silicon anodes, nickel rich cathodes
- Long term energy storage
- Grid Forming

Questions?

PJM Client Management & Services

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Toll Free Telephone: (866) 400-8980

Website: www.pjm.com

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