SAND2012-7372P

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CSP Training Module 6: Major System Operation

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Sponsored by College of the Desert
BrightSource Ivanpah, CA
September 5 and 6, 2012

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Agenda

- 1. Basic Theory of Operation
- 2. Fuel
- 3. Modeling CSP plants
- 4. Basic construction and Design
- 5. Startup and Shutdown
- 6. Major System Operations
- 7. Plant Operation influences on the grid
- 8. Response to Weather Changes
- 9. Water Chemistry
- 10. Plant Performance Measurements
- 11. Safety Concerns

6. Major System Operation

- Boiler Operations
- Turbine Operations
- Generator Operations
- ACC Operations

Boiler Operations

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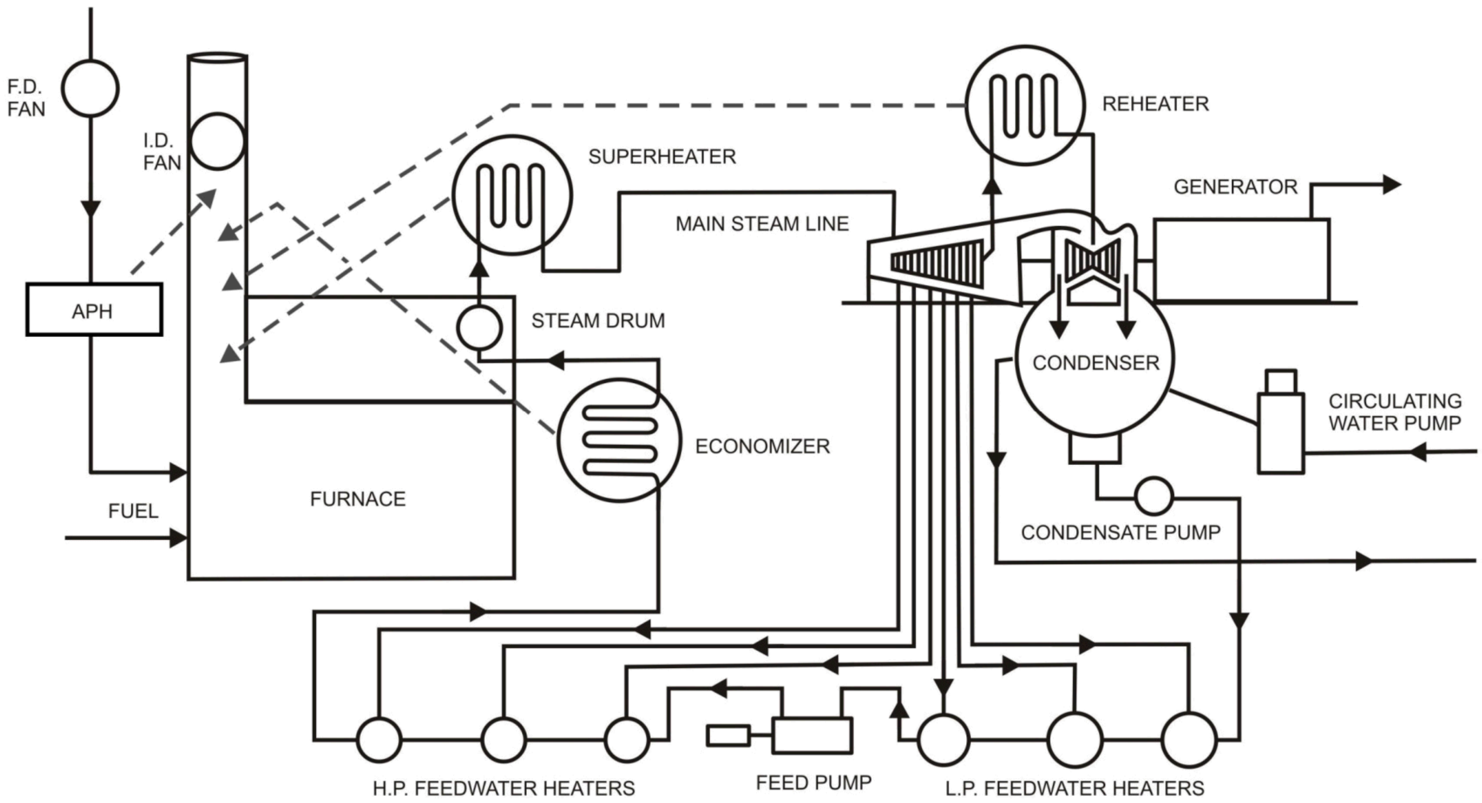
- CSP plants can be hybridized with fossil-fired boilers
- The fossil boiler can either
  - Provide full backup to the receiver during cloudy weather or at night
  - Provide only enough steam for auxiliary steam demands and to keep equipment warm during non-solar periods
- In the case of full backup, the boiler or steam generator operates in parallel with the receiver
  - There may be limitations on the amount of energy generated by fossil due to regulations
  - Example: SEGS plants are limited to 30% hybridization. No more than 30% of the electricity generated can come from natural gas
- When using the boiler, the plant operates similar to a conventional plant.

Boiler Operation

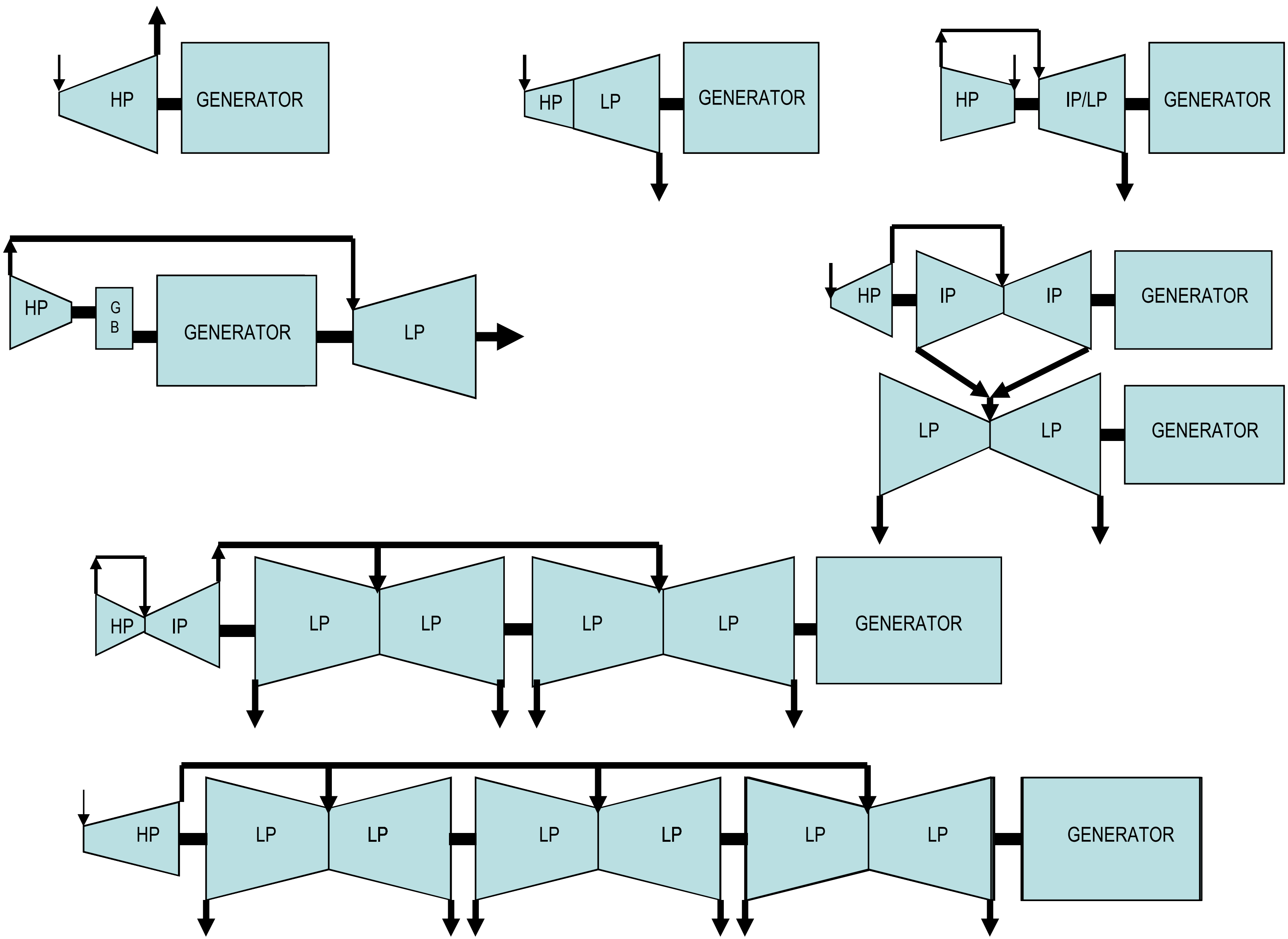
- Augment steam with the fossil boiler to make up steam shortfalls from the receiver during partly cloudy weather
  - Plant must be configured to handle both receiver and boiler steam
  - Need to match pressure and temperature
  - Adapt to rapidly changing conditions
  - Have minimum turn down
  - Boiler will need to be on standby or be able to start without affect system

Boiler for Power Generation



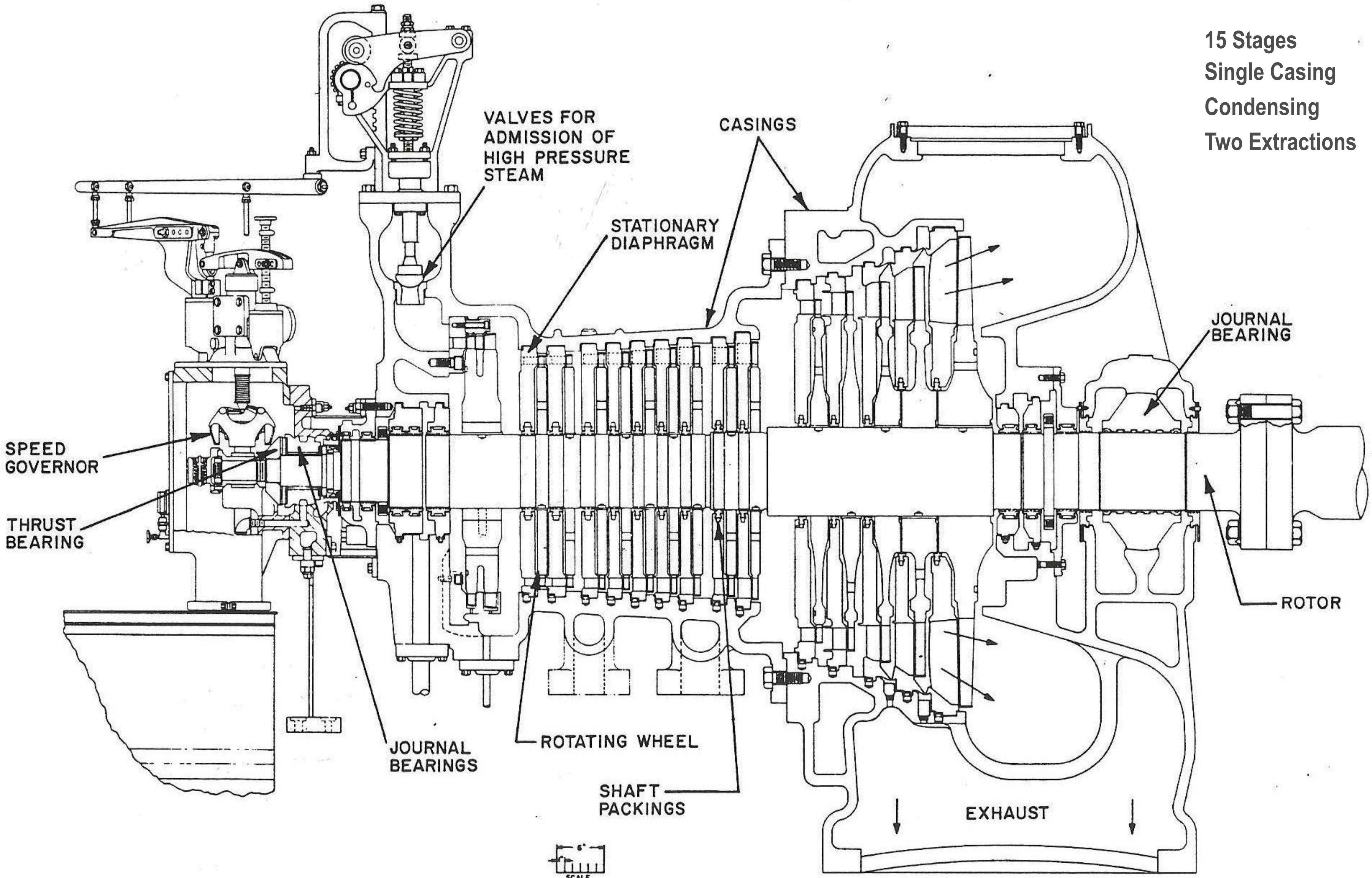
Steam Turbines

Steam Turbine Configurations



Steam Turbine Cross Section

15 Stages
Single Casing
Condensing
Two Extractions

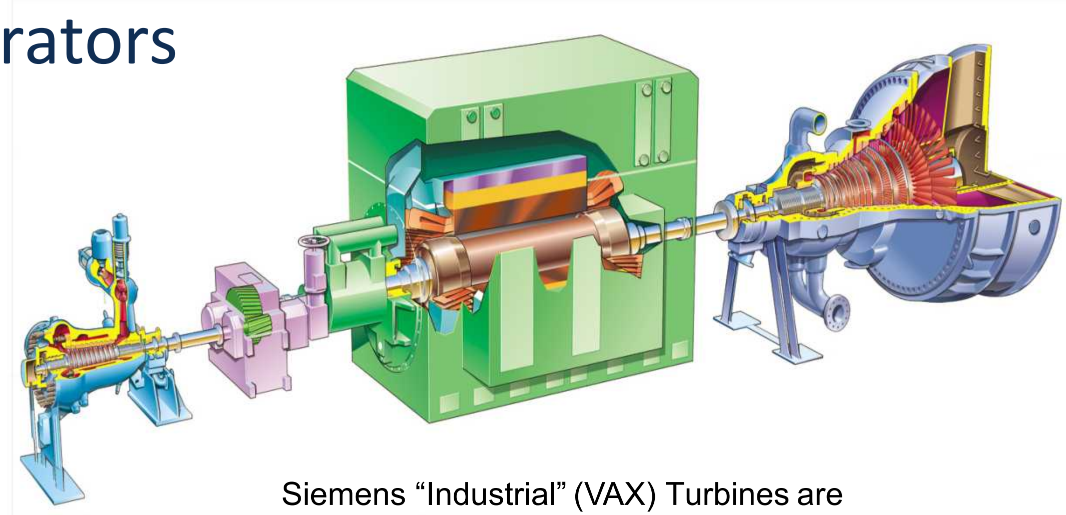


Drawing Courtesy of GE

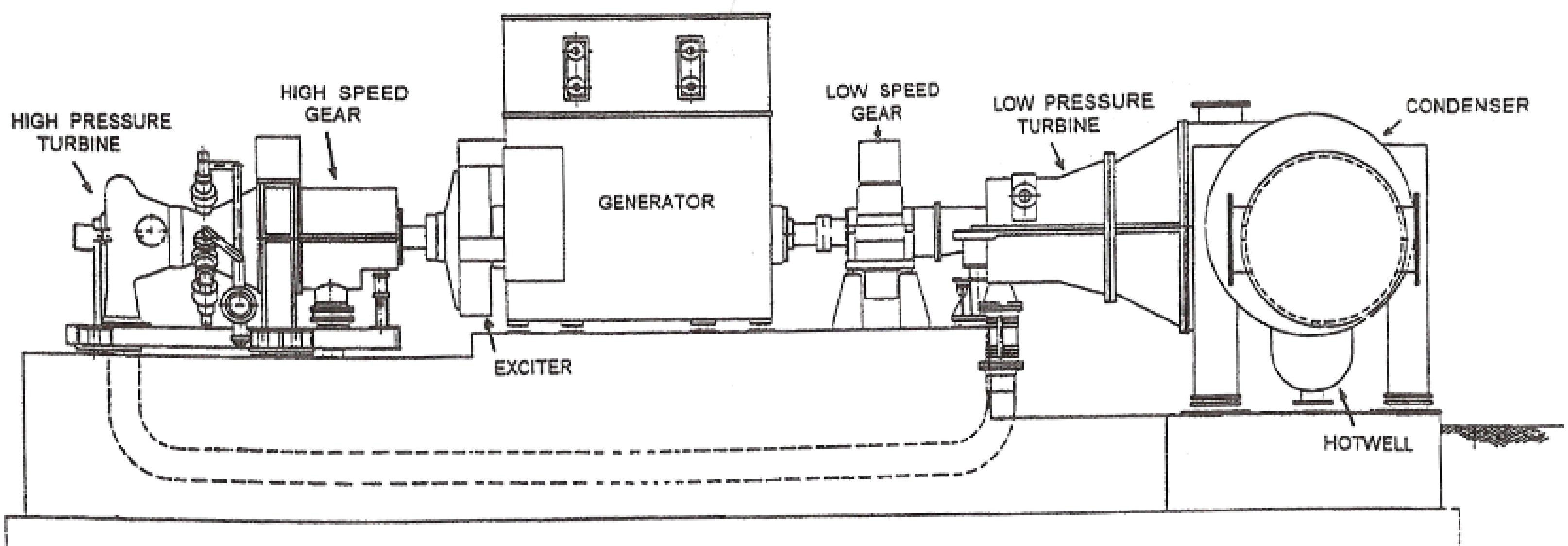
VAX Steam Turbine-Generators

The VAX system was developed in Sweden by Stall in the 1970's. This steam turbine design was comprised of a two "optimized" high speed turbines, one high pressure and one low pressure, operating at different speeds to drive a dual ended generator via two speed reduction gears.

Today's VAX Turbines are sold by Siemens. Their design eliminated the low pressure turbine gearbox but kept an axial flow exhaust condenser.

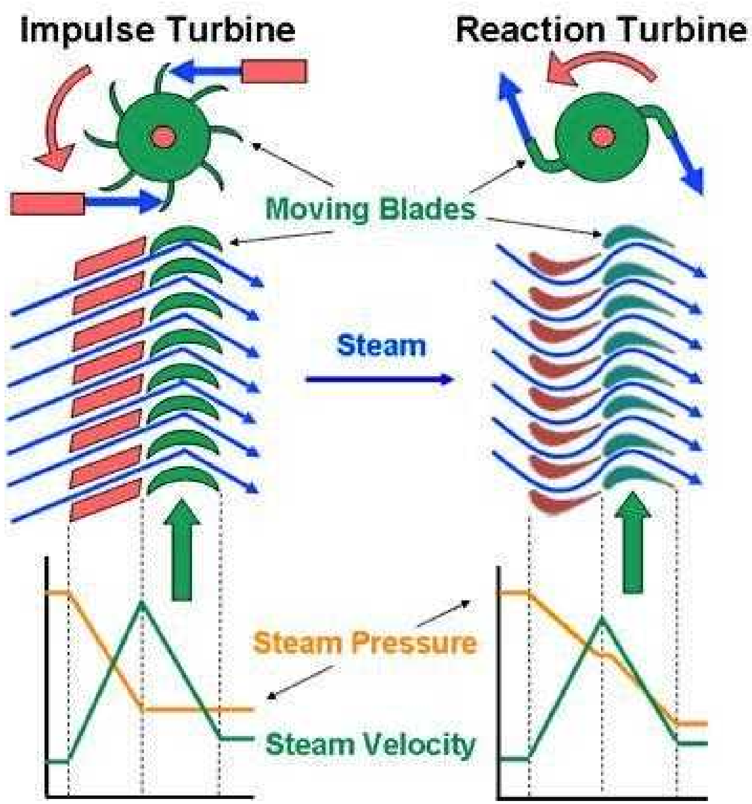


Siemens "Industrial" (VAX) Turbines are a frequent choice for today's CSP plants



A 20 MW VAX Steam Turbine-Generator Set

Basic Turbine Blade Design



Steam Turbine Support Systems

Lube Oil System ______________________________

Control Oil System ______________________________

Turning or Barring Gear ______________________________

Steam Seal System ______________________________

Turbine Extractions ______________________________

Generator Cooling ______________________________

Turbine Speed Control ______________________________

Generator Load Control ______________________________

Steam Admission Valves ______________________________

Turbine Supervisory Instrumentation

Speed & Load

Valve Position

Eccentricity

Vibration

Rotor Position

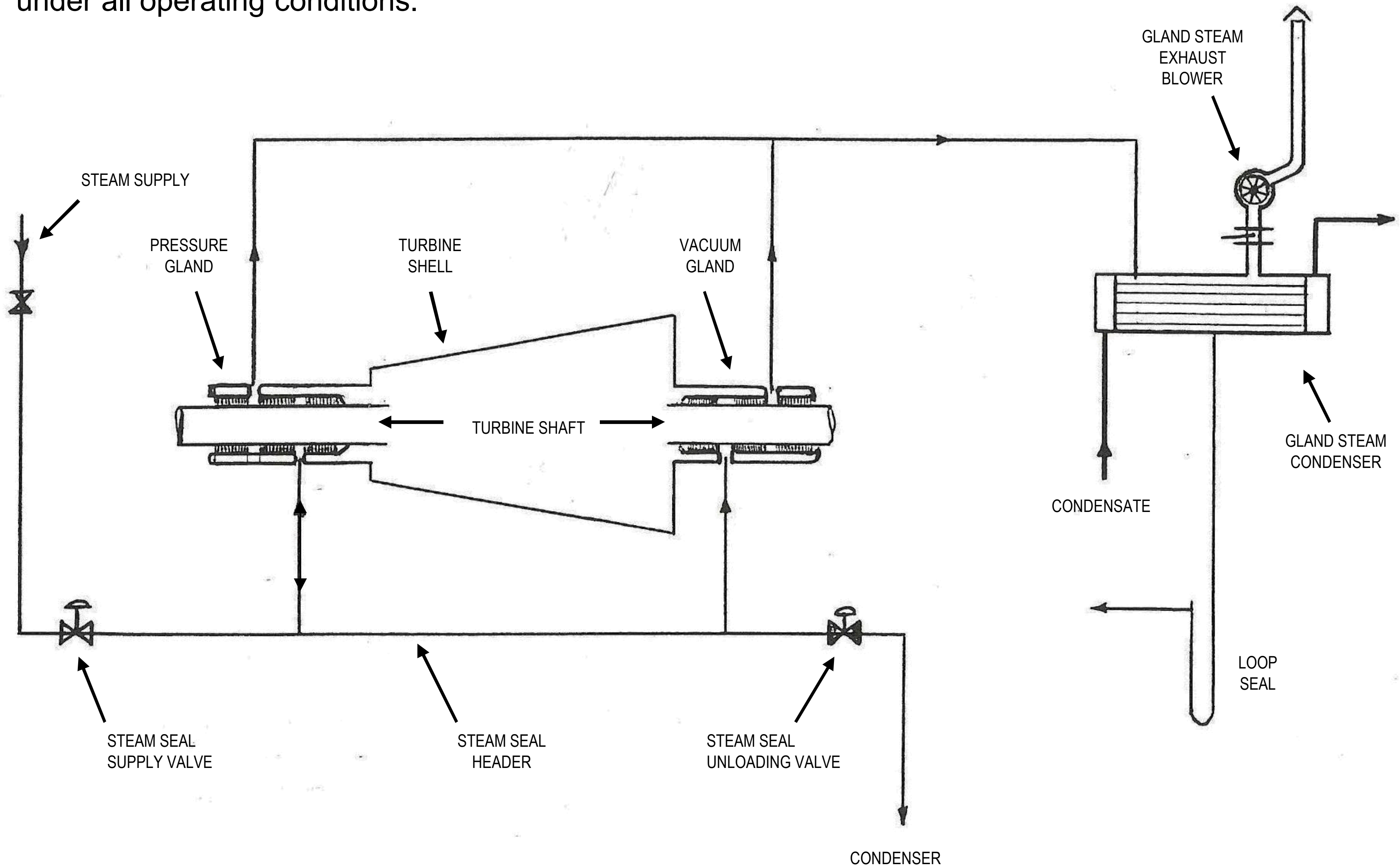
Differential Expansion

Bearing Temperature Thermocouples

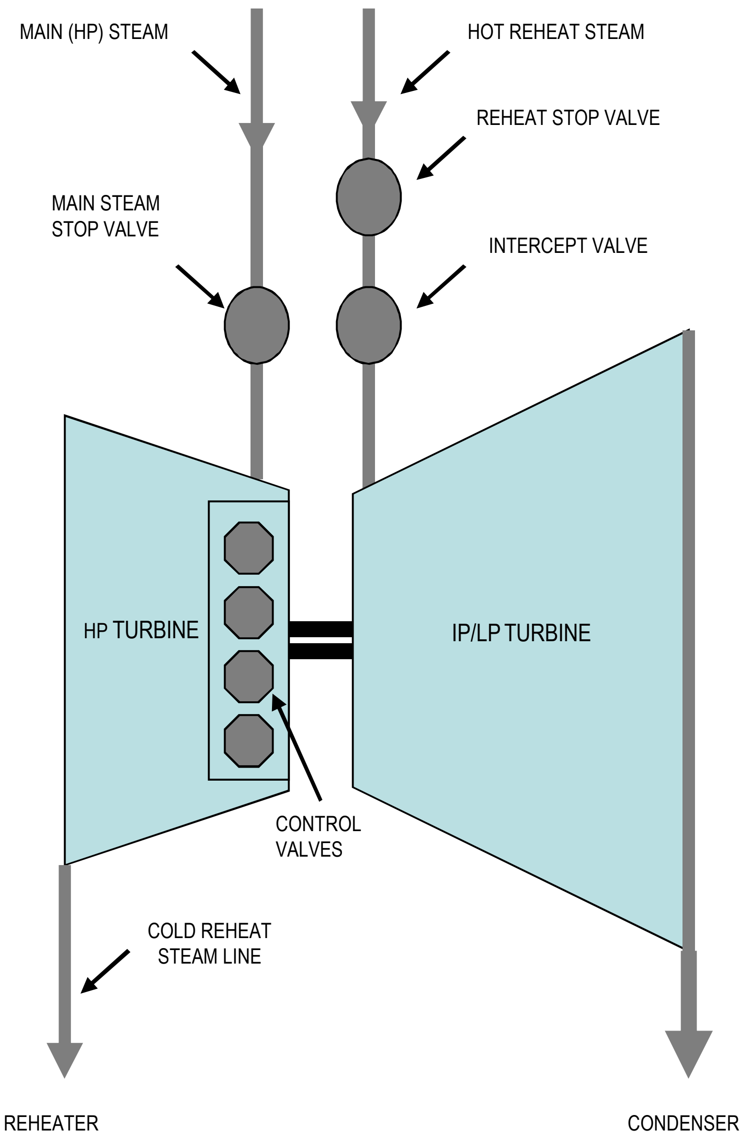
Water Induction Thermocouples

Basic Turbine Steam Seal System

The Turbine's Steam Seal System, also called the Gland Seal System, functions to prevent steam from leaking out of the turbine casing and air from leaking in under all operating conditions.

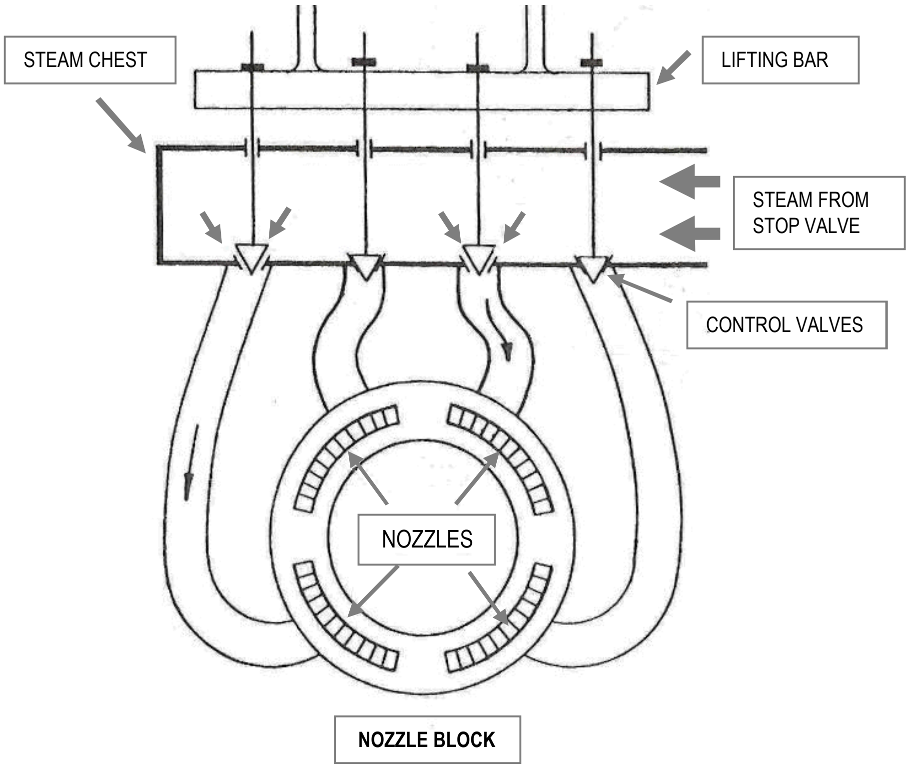


Turbine Steam Admission Valves



CONTROL VALVES

Partial & Full Arc Admission



Utility-Scale Generators

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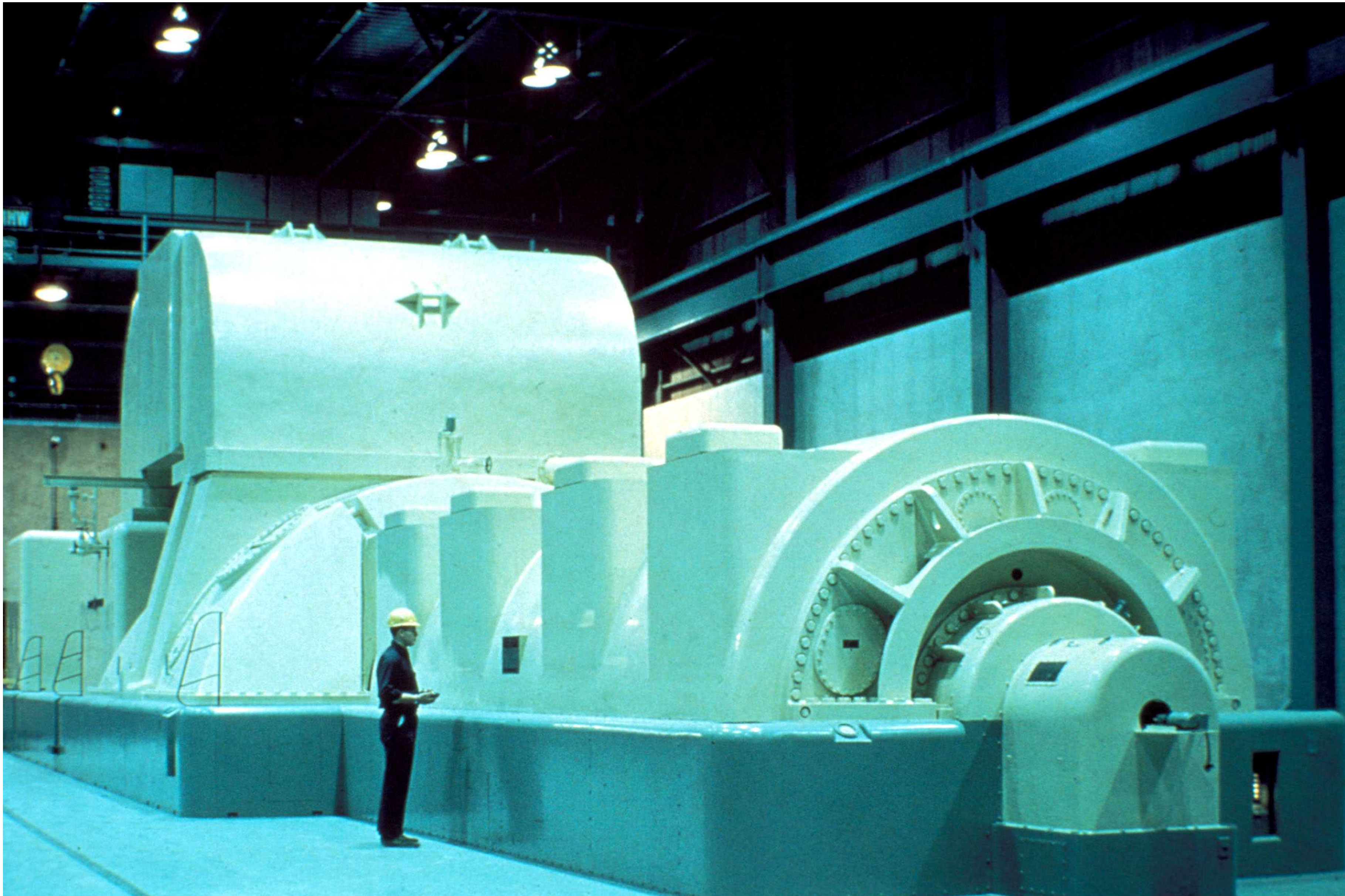

Building Generators

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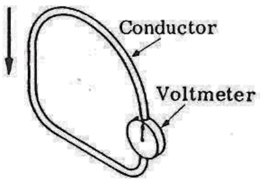
High Desert Power Project

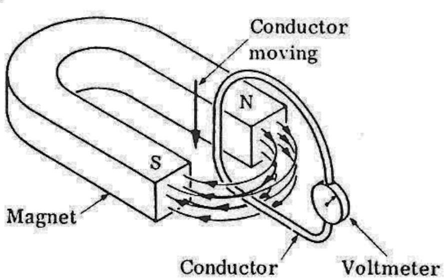
Power Generation Through Magnetism

Conductor Moves
Cutting Magnetic Lines of Force

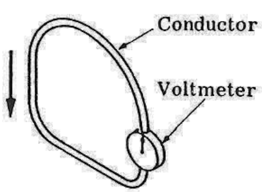
Step 1
Conductor not in lines of force, no voltmeter deflection



Step 2
Conductor in lines of force, voltmeter deflects



Step 3
Conductor not in lines of force, no voltmeter deflection



The Basic Generator

1. A Magnetic Field
2. A Conductor
3. Relative Motion

Improve The Generator

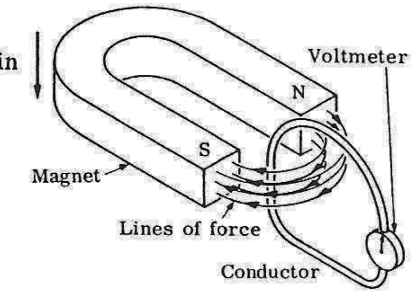
1. A Stronger Magnet
2. More Coils in the Conductor
3. Increase the Relative Motion

Power Industry Generators

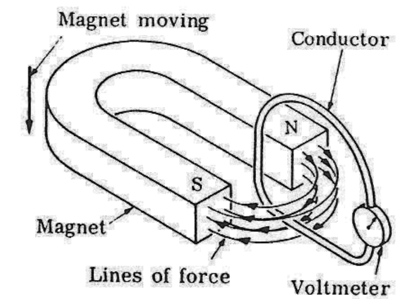
1. Run a Constant Speed
2. The Stator is the conductor
3. The Rotor's an Electromagnet
4. Increasing the strength of the electromagnet produces more electromagnetic lines of force which will be cut by the stator coils during each revolution of the generator's rotor

Magnet Moves
Cutting Magnetic Lines of Force

Step 1
Conductor not in lines of force, no voltmeter deflection



Step 2
Conductor in lines of force, voltmeter deflects



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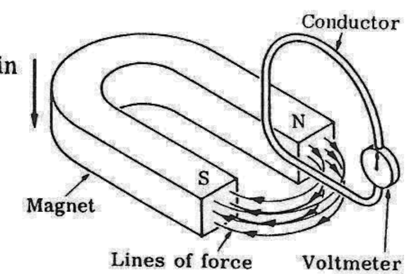
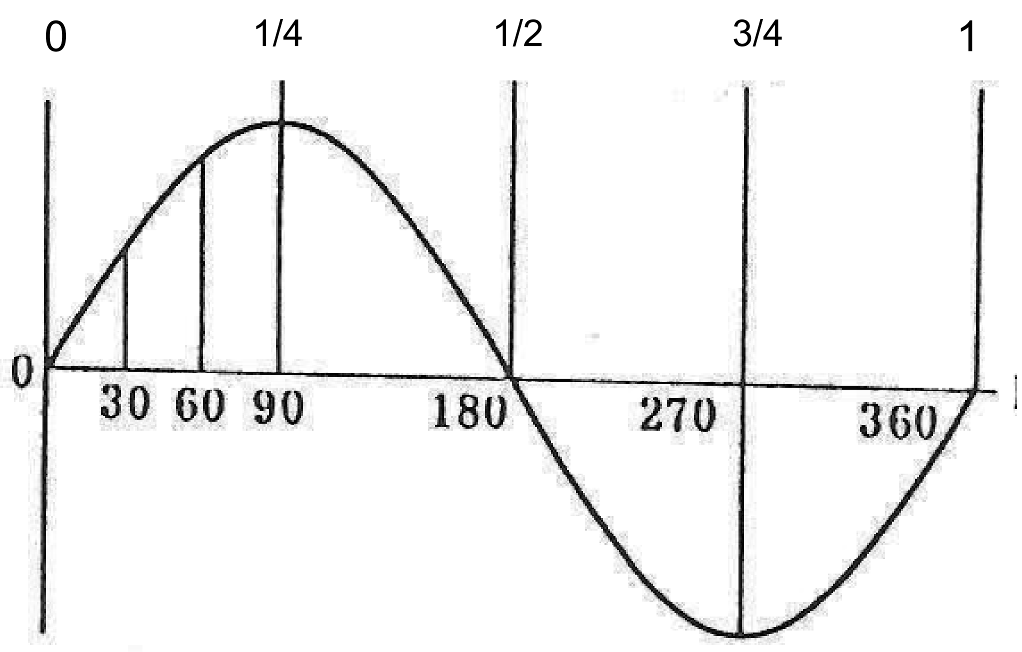


Alternating Voltage – Alternating Current

As we've learned, moving a conductor through a magnetic field causes a voltage to be induced in the conductor. Conversely moving a magnetic field past a conductor will also induce or generate a voltage in the conductor. Either way magnetic or electromagnetic lines of force or flux are being cut.

AC Power is actually Alternating Voltage and Current that is constantly changing in magnitude and direction as the generator's rotating electromagnetic field cuts through the stator's coils. As this occurs voltage polarity and current flow changes and reverses direction twice each cycle or 120 times per second in a 60 Hertz (cycles per second) generator.

<u>One Generator Rotor Revolution = One Cycle</u>



<u>Calculating Generator Frequency</u>

The formula states Frequency in Hertz (F) is equal to the number of Revolutions Per Minute (RPM) times the Number of generator magnetic poles (N) divided by the constant 120.

$$F = \frac{RPM \times N}{120}$$

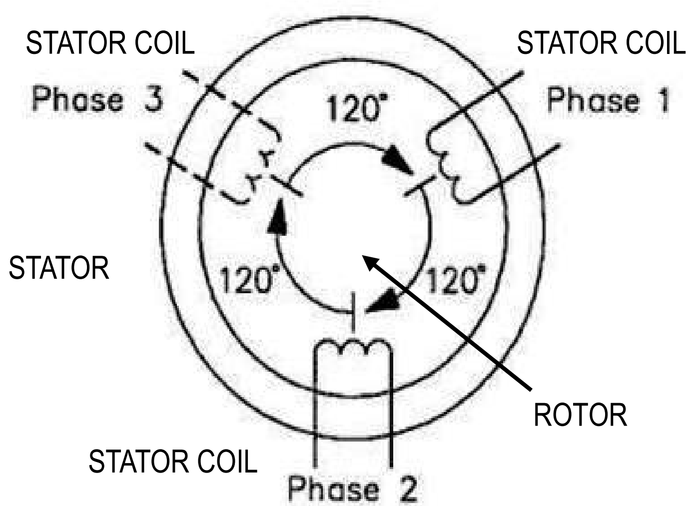
$$F = \frac{3600 \times 2}{120}$$

$$F = \frac{7200}{120} = 60 \text{ Hertz}$$

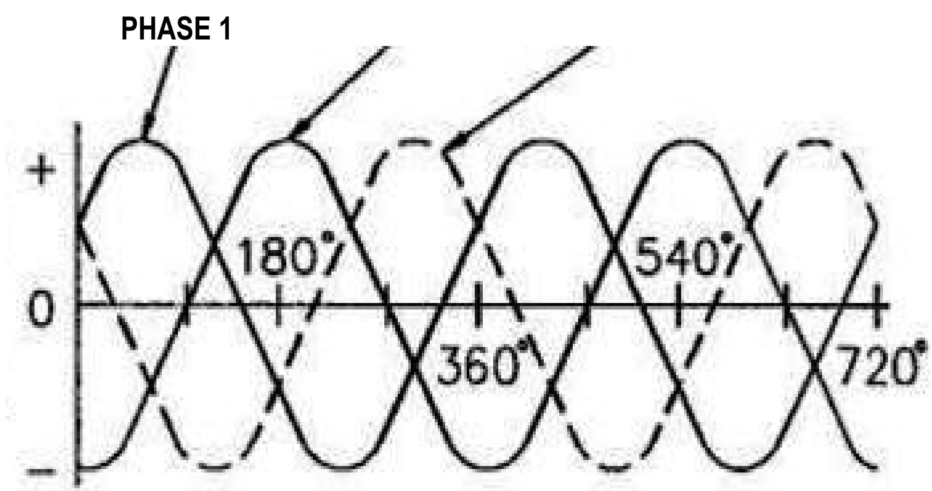
Three Phase Generators

Unlike a basic AC generator with one stator coil, virtually all utility generator's stators are wound with three phases or coils 120 electrical degrees apart.

During one revolution the rotor's electromagnetic field induces voltage into the three stator coils resulting in three separate sine waves. Three phase generators are used because they prove the best balance of power, cost and practical application.



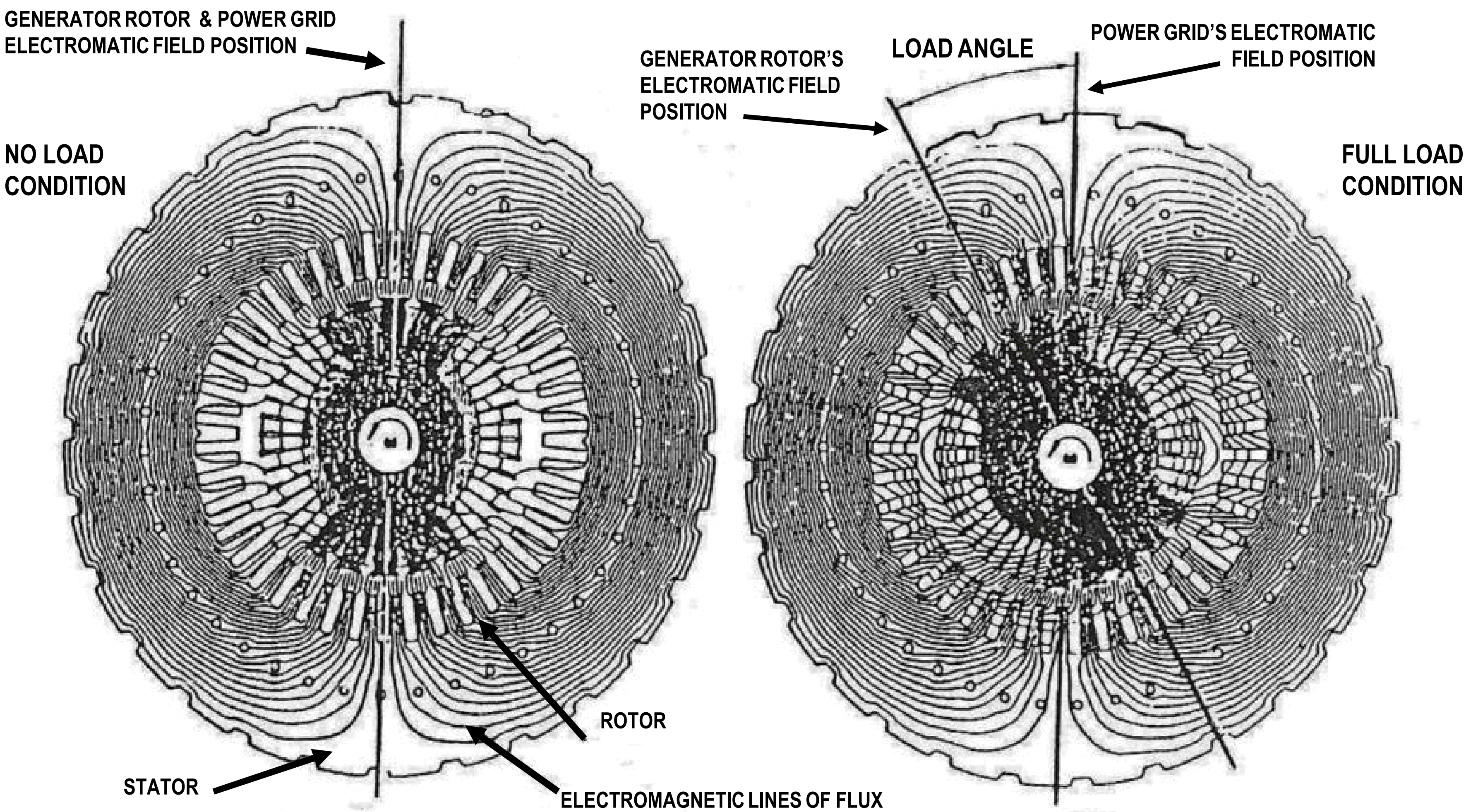
THREE PHASE GENERATOR



THREE PHASE SINE WAVES

Since the turbine-generator is designed to operate at a constant speed and frequency then how does the generator pick up load on the power grid?

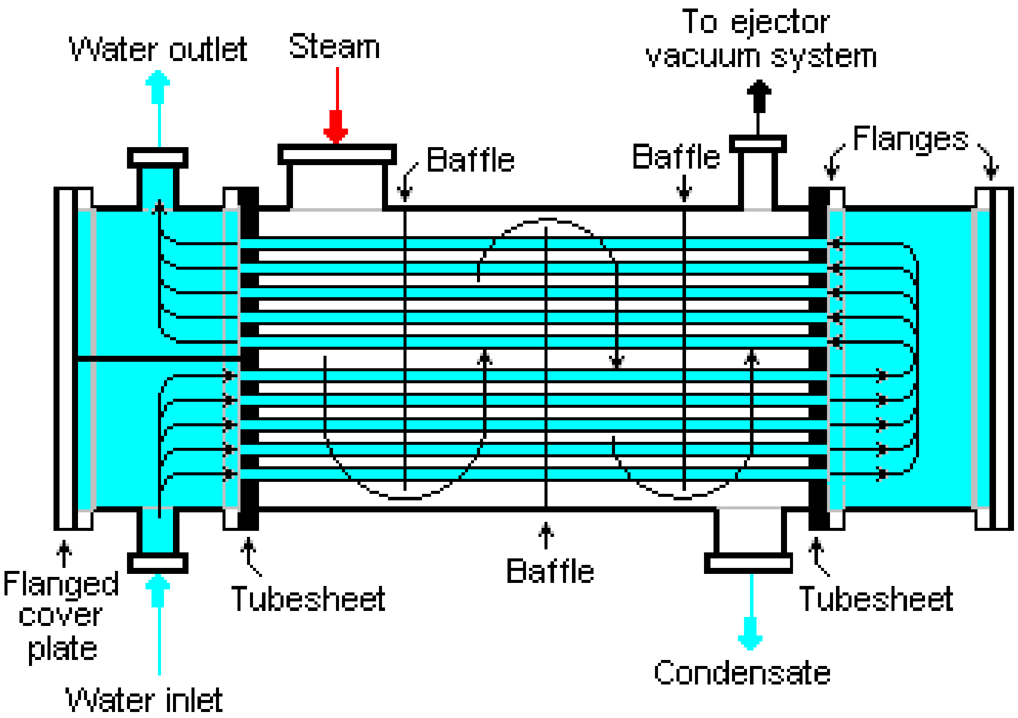
The turbine, which is providing rotating mechanical energy (torque) to the generator shaft, tries to accelerate the generator rotor's speed and therefore its frequency faster than the power grid's frequency. This results in the generator rotor's magnetic field being forced ahead of the stator's magnetic field, which exists because of the 60HZ present on the system/power grid. When the rotor's magnetic field is ahead of the stator's magnetic field by a small angle, but stays in synchronism with it, generator output or "load" increases. The larger the "load angle", the more load the generator carries.



Steam Turbine Condenser

As we now know, the Rankine cycle is a closed loop process where the working fluid (water/steam) is continuously reused. To close the loop, turbine outlet steam (steam that cannot be effectively converted into useful work) is exhausted into a large tube-in-shell heat exchanger called a condenser.

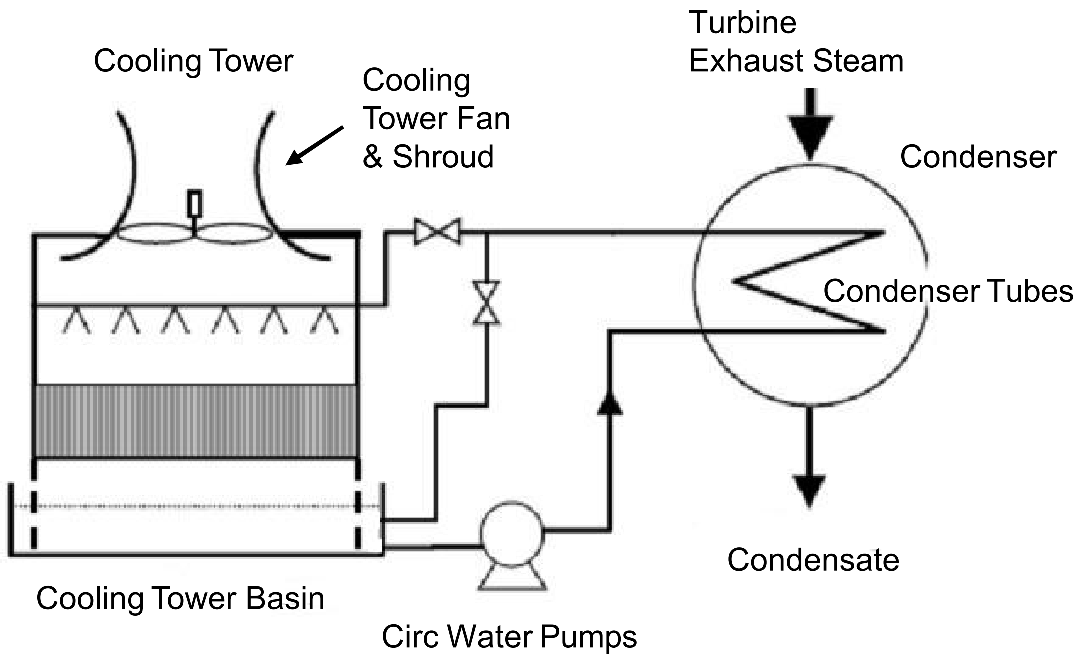
The turbine exhaust steam flows over the condenser tubes which contain cooling water. This cooling water, often called circulating water, or "circ" water, converts (condenses) the turbine exhaust steam back into water called condensate. Since the condenser is designed to be air tight, the condensing of turbine exhaust steam from a large specific volume of approximately 350 ft^3 to condensate with a small specific volume of 0.16130 ft^3 creates a vacuum in the condenser. The creation of the vacuum increases turbine cycle efficiency by lowering the turbine's exhaust pressure (backpressure). The condensate collects at the bottom of the condenser in an area called the hotwell.



From here the condensate is pumped back through the Rankine cycle where it is again pre-heated, made back into steam, superheated and supplied to the steam turbine-generator to produce more electricity.

Steam Condensing Systems

Most Rankine cycle power plants incorporate a "wet" condensing system into their design. Water may be supplied from the ocean, a lake or a river and pumped by high volume, low pressure pumps through the condenser's tubes in a "once through" design back to the source. Circulating Water Systems are common in the Southwest. "Circ" water is pumped from the cooling tower basin through the condenser's tubes (condensing turbine exhaust steam) and back to cooling tower to be cooled and re-circulated.



A BASIC CIRCULATING WATER SYSTEM

"Wet" condenser cooling systems provide the highest level of steam condensing efficiency. However they require large volumes of water and often draw negative public attention because of their large water vapor plumes which are often mistaken for steam.

Dry Steam Condensers (Dry Cooling Towers)

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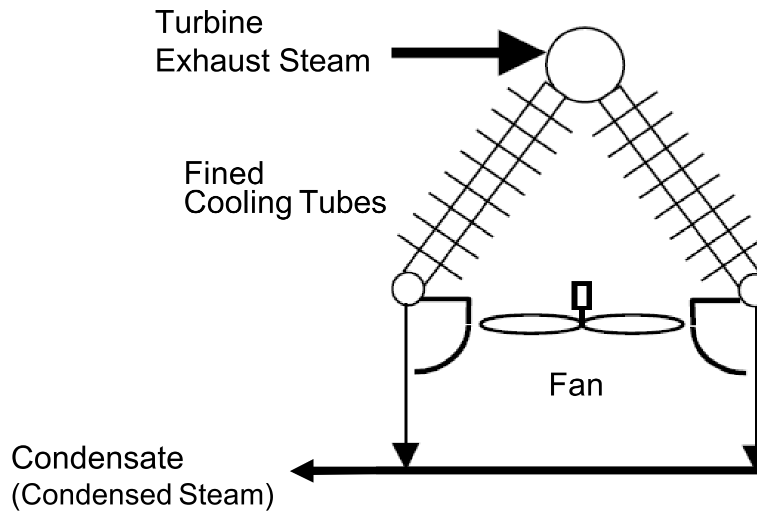

At one time nearly all Rankine Cycle power plants used water cooled condensers. More environmentally friendly designs have resulted in more units with dry steam condenser technology.

Rankine Cycle Power Plant Water Usage

Wet or Dry Cooling.

What's the difference?

WET COOLING DESIGN

250 MWn = 3500 to 4500 acre-feet/year

- 92% for process & plant equipment cooling
- 6% for steam cycle make-up
- 2% for mirror washing & miscellaneous use
- **Almost no loss in generation 40F - 110F ambient**

DRY COOLING DESIGN

250 MWn = 300 to 500 acre-feet/year

- **Reduces plant water consumption by ~90%**
  ~ 6% for steam cycle make-up,
  ~ 4% for equipment cooling, mirror washing & misc.
- Increased plant capital costs ~5%
- Increases the cost of producing electricity ~10%
- Increases parasitics (power used by plant equipment)
- Reduces annual net output >5%
- Reduces power production during hot ambient temps
  ~5% @ 90F ~10% @ 100F ~21% @ 105F

Water Facts

Agricultural = 5 acre-feet per acre per year
1 acre-foot of water = 325,851 gallons
1 acre-foot = 43,560 cubic feet

Residential (4-5 people) = 1 acre-feet per year
1 million gallons = 3.07 acre feet
1 cubic foot of water = 7.48 gallons