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Present Reactor Designs

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Present Reactor Designs

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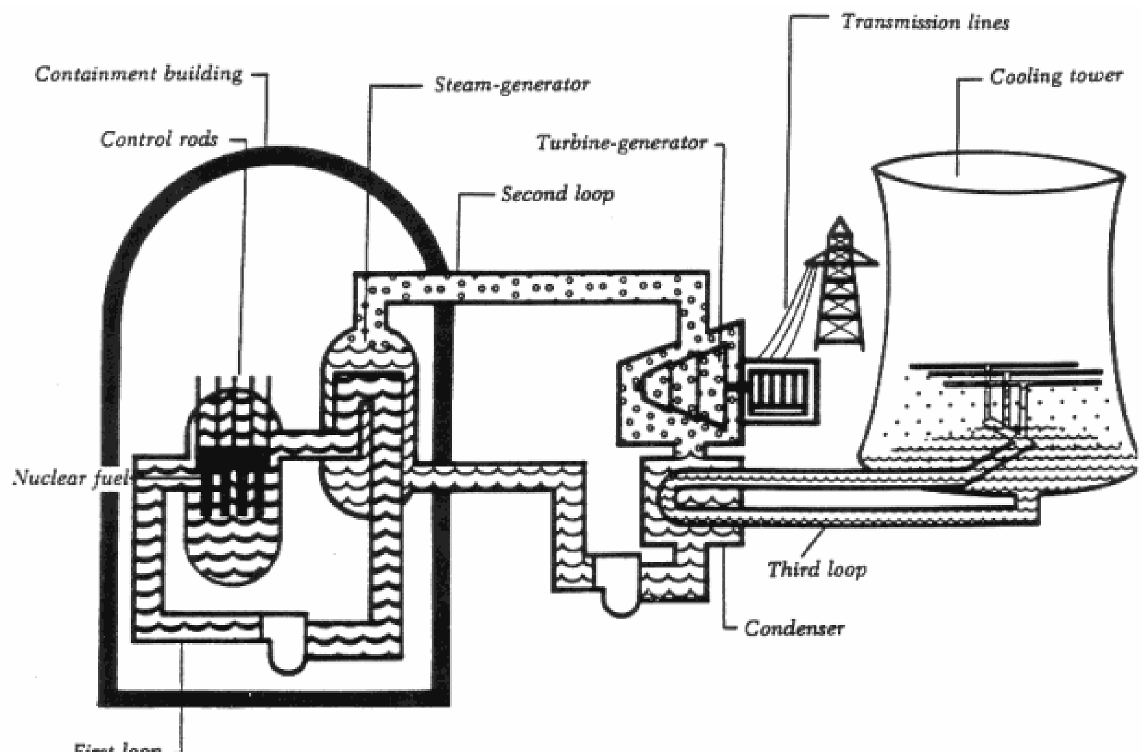
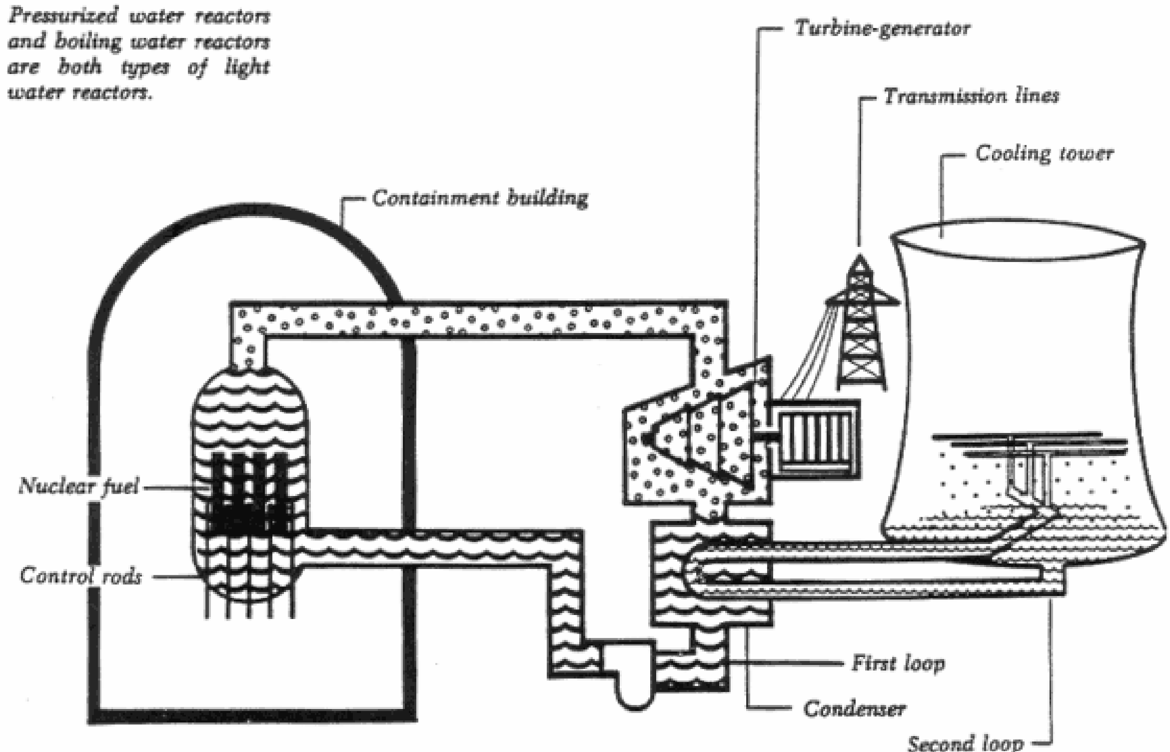
PWR and BWR

The two types of reactors operating in the United States are pressurized water reactors (PWR) and boiling water reactors (BWR). The BWRs are manufactured by General Electric (GE). Thirty-five of the 104 operating reactors are BWRs and the rest PWRs. PWRs are made by Westinghouse (48), Combustion Engineering (14), and Babcock and Wilcox (7). Each type of design has advantages and disadvantages compared to the other type. Below is a simplified diagram of each type. Outside the containment building the systems are essentially the same. We will examine the inside of containment building.



Pressurized Water Reactor



Boiling Water Reactor

Steam Generation

A PWR has a steam generator to separate the radioactive water in the first loop, primary side, from the clean water in the second loop, secondary side. This separation means the secondary side does not have to be shielded for radiation protection. Also, components in the secondary do not become contaminated which allows for ease of maintenance. One disadvantage is the cost of the extra component. A steam generator is typically a U-tube heat exchanger with many tubes. Tube leaks have been a problem in some plants eventually leading to steam generator replacement. Since no boiling is allowed in a PWR, the operating pressure is higher in order for the hot water passing through the tubes to be hot enough to make steam for the turbine. The operating pressure is typically around 2250 psi. A PWR has a pressurizer connected between the reactor and the steam generator. Since water is almost incompressible, in a solid plant any change in temperature would cause a change in pressure. The pressurizer is a vessel half full of water with a steam bubble above the water line. It acts like a surge tank to maintain pressure constant. BWRs do not require a pressurizer.

A BWR operating system pressure is around 1000 psi. This is an advantage because the components do not have to be as strong to contain 1000 psi. However, to get a similar capacity the components are typically larger. Since the steam comes directly out of the reactor, some of the water has undergone neutron activation. The radiation is a personnel hazard during plant operation. Also, corrosion products that become activated are both a radiation and contamination hazard during maintenance activities.

Coolant Flow

A reactor coolant pump (RCP) provides the flow of coolant in a PWR. It is typically a large centrifugal pump with a special shaft seal. The seal is generally in multiple stages and prevents leakage of primary coolant along the pump shaft. Considerable care is given to the seals to prevent damage to them. If a seal fails then a loss of coolant accident (LOCA) could occur.

In a BWR the pump is called a recirculation pump. Steam exits the reactor at the top after passing through moisture or steam separators to remove any water. The water falls back into the reactor. This leads to the term recirculation flow.

Reactivity Control

Reactivity is a term to describe a reactor's departure from criticality. A critical reactor is one where the power level is not changing. In the fission process slow neutrons interact with Uranium-235 (U-235) and produce fission fragments and more neutrons. The new neutrons can interact to cause fission, leak out of the reactor, or be absorbed but not cause fission. The term effective multiplication factor, k *or* k_{eff}, is used to describe this. It is defined as the ration of the number of neutrons produced in one fission generation to the number of neutrons lost through absorption and leakage in the preceding generation.

If $k = 1$ then the reactor is said to be critical

If $k < 1$ then the reactor is subcritical

If $k > 1$ then the reactor is supercritical

A measure of a reactor's departure from critical is called reactivity, R. It can shown as

$$R = \frac{k - 1}{k}$$

An understanding of these terms is necessary to discuss how reactivity is controlled in a PWR and BWR. Both types of reactors have control rods which absorb neutrons. If all the control rods are fully inserted into the reactor the reactor is shutdown. A PWR is typically operated with all the control rods fully withdrawn at power. Boric acid is added to the coolant for reactivity control as fuel is burned up. Boron adsorbs neutrons and the amount of boric acid affects the neutron population. As fuel is burned up the concentration of boron is decreased and is essentially zero at the end of the fuel cycle. Boric acid has one disadvantage in that it is very corrosive with carbon steel. Any leaks of coolant on piping systems must be cleaned up and stopped to prevent corrosion of components.

BWRs on the other hand do not use boric acid. Some of the control rods are inserted during power operation. As fuel is burned up, control rod pattern adjustments are made throughout the fuel cycle to expose more fuel. Since steam is produced in a BWR the control rods are inserted from the bottom of the reactor vessel.

PWRs and BWRs adjust reactivity to account for fuel depletion by different methods. In the next section the method of making power level changes will be presented.

Power Level Changes

In a PWR the coolant coming out of the reactor going to the steam generator is called the hot leg or T-hot. The coolant coming from the steam generator back to the reactor is called the cold leg or T-cold. The average of T-hot and T-cold is called the average temperature or T-avg. In a PWR reactor power is said to follow steam demand. If steam to the turbine is increased, the temperature of the coolant leaving the steam generator is decreased. As colder water enters the reactor it is denser and more neutrons stay in the reactor to cause fission. Power increases until there is an overshoot then the hotter water causes power to decrease. Power is then stable at a higher power level and the difference between T-hot and T-cold is greater. Another way of describing this is in terms of the negative temperature coefficient. As temperature increases then negative reactivity is added.

On the other hand, in a BWR, the turbine is said to be slaved to the reactor. Since boiling is allowed in a BWR there are steam voids or places where there is no water to thermalize neutrons. This is termed the void coefficient. As the number of voids increases, negative reactivity is added to the reactor. Power is increased by increasing coolant flow through the reactor and sweeping more voids out the reactor. As power in the reactor is increased then a pressure controller to the steam turbine opens to increase steam flow and reduce pressure.

Reactor shutdown, trip, or scram

All reactor types have a method to quickly insert all the control rods to stop the power production. It is commonly called a reactor trip or scram. In a PWR the control rods are released and by the force of gravity fall into the reactor. They are also assisted by a spring. In a BWR, the control rods are inserted from the bottom, and use hydraulic force much like force against a piston to insert the rods.

Both reactors have a reactor protection system (RPS) that upon input of a trip signal initiate the action to cause the trip. For example a loss of coolant flow in the primary would create a condition where the heat would not be removed from the reactor. A reactor trip signal would be initiated to quickly insert all the control rods stopping power production. However, not all heat production is quickly stopped as decay heat is produced.

Decay Heat Removal

Immediately following a reactor shutdown when the control rods are fully inserted, the thermal heat produced from the decay of radioactive materials can be significant. It can be as high as 7% immediately after the shutdown. About one hour later it is around 2% and decreases exponentially. After one day it is around 1%. The idea is to keep the reactor core covered with water and cooled. In a PWR it is somewhat more difficult because of the steam generator. Also, in a PWR the coolant must remain sub cooled or below saturation temperature for the corresponding pressure. In a PWR boiling in the core is avoided to prevent formation of a steam bubble resulting in the inability to remove heat. This was a problem during the accident at Three Mile Island. In a BWR it is simpler as boiling can occur.

If available for decay heat removal the normal steam flow path is used to dump steam to the main condenser. Once the main steam lines are isolated then an auxiliary feedwater system (AFW) is used in a PWR. In a BWR, a system called the reactor core isolation cooling system (RCIC) is used. These systems are typically small steam turbines.

Next, consider the case where there is a leak of coolant out of the piping system.

Emergency Core Cooling Systems (ECCS)

When discussing a leak, two things to consider are the size of the leak and if the system stays pressurized. One type of leak is a small leak with the system near operating system pressure. Next, there is a medium leak with a decrease in system pressure. The last type is a large leak with the system depressurized.

PWR

In a PWR there is a high head safety injection (HHSI) or charging pumps (CP) for a small leak. When system pressure drops below 600 pounds, large accumulators charge water into the system. Below a couple hundred pounds, the residual heat removal pumps RHR) or low pressure coolant injection pumps (LPCI) pump water into the system.

BWR

In a BWR the ECCS system is a steam turbine called High Pressure Coolant Injection (HPCI) for a small leak. There are no accumulators but when system pressure starts dropping another system called Automatic Depressurization System (ADS) takes over. An ADS system is a number of safety relief valves that open to depressurize the system in order for the RHR or LPCI system to flood the reactor.

Long Term Cooling

For a large leak the primary coolant will be dumped out the piping system onto the floor of the containment building. For both the PWR and BWR, the suction of the RHR pumps can be aligned to take suction on the containment building floor. The flow path is from the pump into the reactor vessel out the break onto the floor then back to the pump. This can continue as long as needed. Plant modifications in recent years have to make the suction strainer or screens larger in the containment building so that debris during an accident would not prevent the pumps from operating.

Containment Building

The containment building for a PWR consists of a large concrete steel reinforced building. It generally is designed to withstand 60 psi which should contain a large break. The building has an equipment access hatch that is removed during a refueling outage. Some have a smaller escape hatch for personnel. A large overhead crane called a polar crane is in the top of the building. Penetrations into containment have valves or other means to provide for containment isolation in the event of an accident.

Later design BWR containments are similar to a PWR but earlier designs look much different. The early version of a BWR containment was called the Mark I. It consisted of an egg shaped drywell connected to a separate ring called a suppression pool or torus. This was termed primary containment and all of it was contained in a reactor building termed secondary containment. Safety relief valves discharge into the suppression pool which is half full of water.

Electrical System

Each power plant has an electrical system consisting of two or more off-site power sources and on-site power. The off-site power sources are high voltage transmission lines from the electrical grid to the plant. The different sources are often at different voltages and connect to the plant through transformers. The on-site or standby power is power from emergency diesel generators. The generators normally do not run except when needed. In addition each plant has some batteries to provide direct current if alternating current is lost.

During plant startup power is taken from the grid through the off-site power sources through startup transformers to the plant's electrical distribution system. Once the plant is operating and the main generator is producing power it is connected to the grid. Plant loads are supplied through an auxiliary transformer. In the event of some type of accident condition where the reactor and main generator are shutdown, then the emergency diesel generators start to supply power. Depending on the availability of off-site power, a source of power is provided to emergency loads. There are two or more trains or divisions of safety systems.

Radiation

One of the big differences between reactor types is that in a BWR steam comes directly out of the reactor outside the containment building and into the steam turbine. This presents some radiation shielding challenges during operation and complicates maintenance on contaminated systems.

During operation due to the neutron activation of water a large contributor of radiation comes from the decay of N-16 gamma. This occurs from the neutron proton reaction of oxygen in water. It has a short half live of 7 seconds. Once the plant is shutdown this source of radiation is gone after a few half lives. Areas around the main turbine must be shielded during operation.

Also, during operation certain corrosion products become activated. These products stay in the system and present radiation dose and contamination problems during maintenance. One of the main contributors is Cobalt-60 which has a half life of 5.27 years.

PWR Differences

Most of the PWRs are Westinghouse plants. Each reactor vessel is connected to three or more coolant loops with each having a steam generation and RCP. Three loop plants are in the 800-900 megawatt size. Four loops plants are in the 1100-1200 megawatt size. Most similar to a Westinghouse plant is a Combustion Engineering plant. Some of these are only two loops with two RCPs per loop.

The accident at Three Mile Island was a B & W plant. Not many of this type were built and no more are planned. The steam generator is a once through generator. The steam that comes out of this type steam generator undergoes some superheating. Also, a B &W plant has an integrated control system that tries to anticipate a change in power level and make the anticipated changes needed.

Regulations

The regulation concerning nuclear power plants are found in the Code of Federal Regulations. They can be found in NRC Regulations, Title 10 Code of Federal Regulations.

http://www.nrc.gov/reading-rm/doc-collections/cfr/

Under Part 50, Domestic Licensing of Production and Utilization Facilities, the General Design Criteria for Nuclear Power Plants, Appendix A, can be found.

For example, under Criterion 35, the requirements for emergency core cooling can be found.

http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appa.html

Quality assurance requirements are given in Appendix B. There are 18 items a quality assurance program is required to contain. Some of these are design control, inspections, audits, and corrective action. Usually a plant organization will implement procedures covering each of the 18 items.

Summary

The basic differences between the PWR and BWR have been presented. The 104 operating reactors are one of these types. There are different control systems for changing power and accounting for fuel depletion. Each type has similar systems for removing decay heat, emergency core cooling, and electrical power.

List of Acronyms

ADS	Automatic Depressurization System
AFW	Auxiliary Feedwater
B &W	Babcock and Wilcox
BWR	Boiling Water Reactor
CE	Combustion Engineering
CP	Charging Pump
ECCS	Emergency Core Cooling System
GE	General Electric
HHSI	High Head Safety Injection
HPCI	High Pressure Coolant Injection
LOCA	Loss of Coolant Accident
LPCI	Low Pressure Coolant Injection
PSI	Pounds per Square Inch
PWR	Pressurized Water Reactor
R	Reactivity
RCIC	Reactor Core Isolation Cooling
RHR	Residual Heat Removal
RCP	Reactor Coolant Pump
RPS	Reactor Protection System

Table of Differences

Item	PWR	BWR
Decay Heat Removal	AFW	RCIC
Steam produced	In steam generator	In Reactor
Operating pressure	2250 psi	1000 psi
Reactivity change for fuel use	Boric acid concentration	Rod pattern adjustment
Power change	Steam demand	Recirculation Flow rate
Primary flow provided by	Reactor coolant pump	Recirculation pump
Turbine shielded	No	Yes
Small high pressure leak	HHSI or CP	HPCI
Medium pressure leak	accumulators	Initiates ADS
Large leak	RHR or LPCI	RHR or LPCI
Control rod entry	Top of reactor	Bottom of reactor