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Study of Functioning of Nuclear Power Reactors

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Abstract – *Energy and power generation play a crucial role in economic development. There are many sources of power generation. Natural gas, petroleum, coal, oil, etc. but these sources demands an alternative source of energy because coal and petroleum are non-renewable sources and they emit huge amount of carbon emissions in environment. Abundant power can be generated by fission of atoms. Atoms are considered as limitless source of energy and hence, from a small mass, huge amount of energy can be extracted, but this process is quite difficult to handle and complicated process. This paper summarizes all components and processes involve in functioning of conventional nuclear power reactors, and comparing the changes made during past time.*

Key Words: Uranium, Coolants, Reactor core, Brayton cycle, Radioactivity, Fission, Moderation.

1. INTRODUCTION

In nuclear power reactor, energy released during splitting up of atoms of certain elements, is used as heat to produce steam to generate electricity. The basic principle of nuclear reactor is the energy released from continuous fission of the atom of fuel is harnessed as heat in either gas or liquid and is used to produce steam. This steam is used to drive turbine which are connected to electric generator like in most fossil fuel plants. The main design is the Pressurised Water reactor (PWR), having water at over 300^{O}C under pressure in its primary heat transfer circuit, and generates steam in secondary circuit, while the less numerous Boiling Water Reactor (BWR) generates steam in its primary circuit in upper region of reactor core at similar pressure and temperature. Water is used as both Coolant as well as moderator in both the reactors.

1. BASIC COMPONENTS OF NUCLEAR REACTOR

1.1 Fuel

In most of reactors, Uranium is used as nuclear fuel and also very common element in crust of earth (as common as Tin or Zinc). Usually pallets of Uranium Dioxide (UO_2) are arranged in tubes to form fuel rods then arranged into fuel assemblies in the reactor core. Nearly 51,000 fuel rods with 1.8million pellets are used in a 1000MWe class PWR. Thorium can also be utilized as fuel for CANDU reactors, once they started using a fissile material such as U-235 or Pu-239, then Th-232 atom capture a neutron to become U-235 during reaction, which continues the reaction. [6]

1.2 Neutron Moderator

Neutron moderator used in nuclear reactor for slow down the fast neutrons to make them more effective in the fission chain reaction. Material used for moderation need to very specific set of properties, a moderator cannot absorb neutrons itself. However it should be able to slow down neutron to an acceptable speed. If collisions between neutron and nuclei are elastic collision it implies that the closer in size the nucleus of an atom is to a neutron, the more neutrons will be slowed, for this lighter elements tend to be more effective moderators. Material (typically) used for moderation includes Heavy water, Light water and Graphite.

Light water, large amount of Hydrogen is present in water. Hydrogen works as neutron moderator because its mass is almost identical to that of neutron. This means one collision will significantly reduce the speed of neutron because of laws of conservation of energy and momentum. The major drawback of using Hydrogen is, it has relatively high neutron absorption cross-section because of its ability to form Deuterium.

Heavy water, is similar to light water, but it contains Deuterium atom its neutron absorption cross section is much lower. Its major drawback is its high production cost as it is synthesis using Girder-Sulfide process.

Graphite is thermally stable and conducts heat as well but it needs to be in pure form. At high temperature graphite can react with oxygen and CO_2 in reactor and decrease its effectiveness, and also graphite is lower in strength and density which could cause it to change dimensions in reactor. [5]

Properties of common Neutron Moderators [8]

	Neutron scattering cross-section (σ_s) in barns	Neutron absorption cross-section (σ_a) in barns
H_2O (Light water)	49	0.66
D_2O (Heavy water)	10.6	0.0013
Graphite	4.7	0.0035

1.3 Control Rods

Control rods are used to absorb neutron so that nuclear chain reaction can be slowed down or stopped completely by inserting them slightly or accelerated by removing them slightly. On an average 2.5 neutrons are releases in fission of U-235, but only one neutron is needed to sustain the nuclear chain reaction at a steady rate, control rods absorbs these extra neutrons and can be used to adjust power output of reactor. When inserted the standard amount, their position is at criticality. If rod pushed in the number of neutrons decrease along with power output and reactor is below criticality and opposite if rods pulled out as fission goes beyond criticality. The measure of how well a material absorbs cross section or σ_a, measured in **barns** (equals to 10^{-28} sq. meters). Control rods made by using Cadmium, Hafnium or enriched Boron. [9].

1.4 Coolants

Reactor coolant extracts the heat from fuel elements in the reactor core and transfers it to the steam generator (boiler) where it give up the heat to water carried in pipes to turn it into steam. Flow rate of coolant decides the efficiency of this process. The coolant is heated to the highest acceptable temperature to increase the plant's efficiency by providing steam to turbines at high temperature and pressure. In BWRs there is secondary coolant circuit where the water becomes steam, while PWR has two to four primary coolant loops with pump driven by steam or electricity. China's Hualong One design has three, each driven by 6.6MW electric motor (weighing 110 tonnes each). [6]

2. FUELLING OF A NUCLEAR POWER REACTOR

Refueling is at intervals of 12 to 24 months. If graphite or D_2O is used as moderator, it is possible to run a power reactor on natural Uranium instead of enriched Uranium. Natural Uranium has the same element composition as it was mined i.e. 0.7% U-235, over 99.2% U-238, enriched Uranium has proportion of isotope U-235, increase by enriched, commonly to 3.5 - 5.0%. Some of the U-238 is changed to Pu-239 ends up providing about 1/3 of the energy from the fuel, during chain reaction.

The fuel is ceramic Uranium Oxide (UO_2 with melting point 2800^{o}C). The fuel pellets usually about 1cm in diameter and 1.5cm long are arranged an a Zirconium alloy (known as **Zircaloy**) tubes to form a fuel rod, the Zirconium being corrosion resistant, hard and transparent to neutrons, generally rods are about 4m long. A fuel assembly of BWR might be contain about 320Kg and PWR 655Kg, and in both about 100Kg of Zircaloy is involved.

Burnable poisons are often used in fuel or coolant to even out the performance of the reactor over time from fresh being loaded to refueling. These are neutron absorbers which decay under neutron exposure, compensating for the progressive build up neutron absorbers in the fuel as it is burned and hence allowing higher fuel burn-up (In GW days per tonne of U). Gadolinium is used in naval reactors and it is incorporated in the ceramic fuel pallets. An alternative is Zirconium diboride Integral Fuel Burnable Absorber (IFBA) as coating on pellets. Gadolinium, mostly at up to 3g oxide per Kg of fuel, requires slightly higher fuel enrichment to compensate for it, and also after burn up of about 17GWd/t it retains about 4% of its absorptive effect and does not decrease further. The ZrB_2 IFBA burns away more steadily and completely, and has no impact on fuel pellet properties. [6].

3. POWER RATING OF A NUCLEAR REACTOR

Nuclear plant reactor power outputs are quoted in three ways.

1) **Thermal MWt**, which depends on the quantity of steam is produced and design of actual nuclear reactor.
2) **Gross electric MWe**, which indicates the power produced by attached steam turbine and generator and also the ambient temperature condenser circuit, is taken into account, i.e., cooler means more electric power, warmer means less.
3) **Net electric MWe**, which is power available to sent out from plant to grid, after deducting electrical power needed to run the rest of the plant.

Gross Mwe and Net electrical MWe may slightly vary from summer to winter, so normally summer figure or an average figure is used. Watts Bar PWR in Tennessee is reported to run about 1125MWe in summer and 1165MWe net in winter, due to different condenser cooling water temperature.

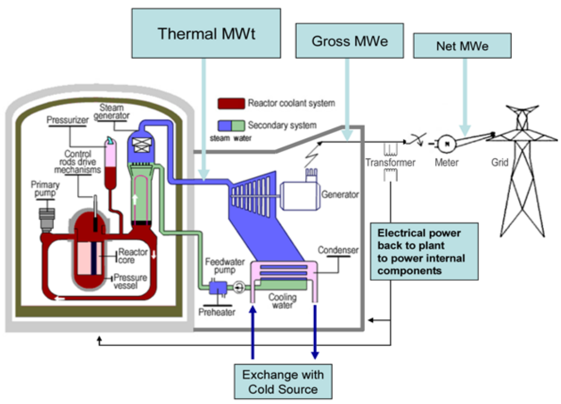


Fig-1: Power rating locations in a nuclear power plant [6]

Relationships between these ratings are expressed in two ways:

1.) Net efficiency percentage, the ratio of net MWe achieved to thermal MW. This is little lower and allows for plants usage. Generally net MWe is used for operating plants and gross MWe for those under construction or proposed.

2.) Thermal efficiency percentage, the ratio of gross MWe to thermal MW. This relates to difference in temperature between steam from reactor and cooling water. It is often 33 – 37% in light water reactors, reaching 38% in the latest PWRs. [7]

4. PRIMARY COOLANTS

Generally gas, water, salt, light and heavy metal are used as coolant:

Water or **heavy water** is maintained at very pressure about 1000-2200psi (7-15MPa, 150atm) to enable it to function well above 100^{O}C up to 345^{O}C as in present reactors. However supercritical water around 25MPa can give 45% thermal efficiency as at some fossil fuel power plant with outlet temperature 600^{O}C and at supercritical level, i.e., 30+ MPa, 50% may be attained, water at 75atm has good heat capacity (about 4000KJ/m^3), hence more effective than gas for removing heat though its thermal conductive is less than liquid alternatives.

Helium is used at 1000-2000psi (7 – 14MPa) to maintain sufficient density for efficient operation, but at 75atm its heat capacity is only about 20KJ/m^3. It can be used in Brayton cycle to drive a turbine directly since there are engineering implification from high pressure.

Carbon dioxide has better thermal conversion efficiency since it is denser than helium. Chances of leak in CO_2 are readily less than helium. Supercritical CO_2 is used for Brayton cycle.

Sodium is generally used in Fast Neutron Reactors (FNRs) at around 550^{O}C, it melts at 98^{O}C and boils at 883^{O}C at atmospheric pressure, it gas has high thermal conductivity and high heat capacity about 1000KJ/m^3 at 2atm. Normally water/steam is used in secondary circuit to drive turbine (Rankine cycle) at lower thermal efficiency than Brayton cycle. Sodium is non corrosive to metal used in fuel cladding or neither primary circuit nor the fuel itself, if there is damage in cladding, it reacts exothermally with water or steam to liberate hydrogen. Sodium has a low neutron capture cross-section, but some of Na-23 become Na-24. Which is beta-emitter and very gamma-active with 15 hrs of half cycle, hence some shielding is required. In large reactor, with about 5000t sodium per GWe, Na-24 activity reaches an equilibrium level of nearly 1TBq/Kg. NaK eutectic which is liquid at room temperature (about 13^{O}C) may be used as coolant if reactor needs to be shut down frequently, but potassium is pyrophoric, which increase the hazard. Sodium is about 6 times more transparent to neutrons than lead.

Lead or lead-bismuth eutectic in FNRs are capable of higher temperature operation at atmospheric pressure. They have greater efficiency due to greater spacing between fuel pins, which are allows coolant flow by convection for decay and heat removal, and since they do not react with water, the heat exchanger interface is safer, and they are also transparent to neutrons. They do not burn when expose to air. However, they are corrosive of fuel cladding and steels, which originally limited to temperature to 550^{O}C, in future 800^{O}C is envisaged with the second stage of Generation IV, using oxide dispersion-strengthened steel. Lead and Pb-Bi have much higher thermal conductivity than water, but lower than sodium. Lead has limited activation from neutrons, Pb-Bi yields toxic Polonium (Po-210) activation product, and this is an alpha emitter with half life of 138 days. Pb-Bi melts at relatively low temperature 125^{O}C hence eutectic and boils at 1670^{O}C, Pb melts at 327^{O}C and boils at 1737^{O}C but it is more abundant and cheaper to produce than bismuth, Pb-Bi cooled fast neutron reactors is likely to produce limited power, total of 50-100GWe. The Gen-4-module (Hyperion) reactor will use Pb-Bi eutectic which is 45% Pb, 55%Bi, secondary circuit generation steam is likely.

Salts: fluoride salts have boiling point around 1400^{O}C at atmospheric pressure, so allow several options for use of heat, including using helium in a secondary Brayton cycle circuit with thermal efficiencies of 48% at 750^{O}C to 59% at 1000^{O}C for manufacture of hydrogen. Fluoride salts have high boiling point, low vapour pressure, high volumetric heat capacity (4670 KJ/m^3 for FLiBe, higher than water at 75atm), good heat transfer properties, low neutron absorption, are not damaged by radiation chemically very stable so absorb all fission products well and do not reacts violently with air or water. Some gamma-active F-20 is formed by neutron capture, but has very short half life of 11 seconds.

Lithium-beryllium fluoride Li_2BeF_4 (FLiBe) salt is a eutectic version of LiF (2LiF+BeF2) which solidifies at 459^{O}C and boils at 1430^{O}C. It is favoured in AHTR/FHR primary cooling and when uncontaminated has low corrosion effect. LiF without the toxic beryllium solidifies at about 500^{O}C and boils at about 1200^{O}C. FLiNaK (LiF-NaF-KF) is also eutectic and solidifies at 454^{O}C and boils at 1570^{O}C.

There is some radioactivity in the cooling water flowing through the core of water reactor, due mainly to the activation product nitrogen-16 formed by neutron capture from oxygen. N-16 has a half life only 7 seconds but produces high energy gamma-radiation during decay. It is the reason that access to a BWR turbine hall is restricted during actual operation.[1]

5. CONVENTIONAL NUCLEAR REACTORS

5.1 Pressurized Water Reactor (PWR)

PWRs are originated as a submarine power plant and uses water as coolant and moderator. Basic design contains a primary cooling circuit which flows through the reactor core under very high pressure and secondary circuit in which steam is generated to drive the turbine. In Russia, PWRs known as VVER types- water moderated and cooled. A PWR has fuel assemblies of 200-300 rods each, arranged vertically in the core, and a large reactor would have about 150-250 fuel assemblies with 80-100 tonnes of Uranium. In reactor core, water reaches up to 325°C which is kept under pressure 150atm to prevent it from boiling, pressure is maintained by steam in a **pressuriser.** Water is also the moderator in primary circuit. If steam is created in primary circuit, the fission reaction would slow down. This negative feedback effect is of the safety feature. The secondary shutdown system involves adding Boron to the primary circuit. The secondary circuit is kept under less pressure and the water boils in the heat exchangers which thus steam generates. Steam drives the turbine to produce electricity and is then condensed and returned to the heat exchangers in contact with primary circuits.[6]

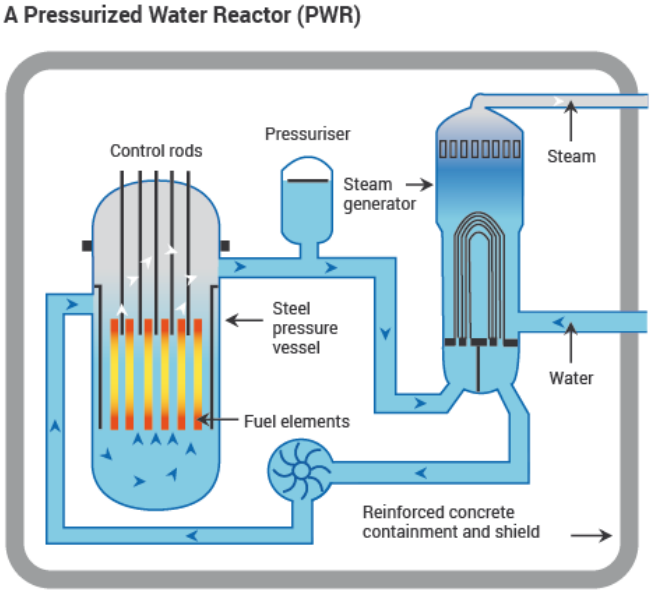


Fig – 2: Pressurized Water Reactor[6]

5.2 Boiling Water Reactor (BWR)

This reactor is similar to PWR, except that there is only a single circuit in which water at lower pressure (around 75 atm.) so that it boils in the core at about 285°C. the reactor is designed to operate with 12-15% of the water in top part of core as steam, and hence with less moderating part of core as steam, hence with less moderation effect, good efficiency there.

The steam pass through steam separators above core and then directly to turbine (which are part of reactor circuit). The water around the core is always contaminated with traces of radionuclide, therefore turbine is shielded and radiological protection is provided during maintenance. Most radioactivity in water is very short-lived, generally N-16, with 7 sec-half life, so the turbine hall can be enterable soon after the reactor is shut down for maintenance. A BWR fuel assembly comprises 90-100 fuel rods, and there are up to 750 assemblies in reactor core, holding up to 140 tonnes of uranium. The primary emergency system uses control rods while secondary system involves restricting water flow through the core so that more steam in top part of core is formed which reduces moderation.[6]

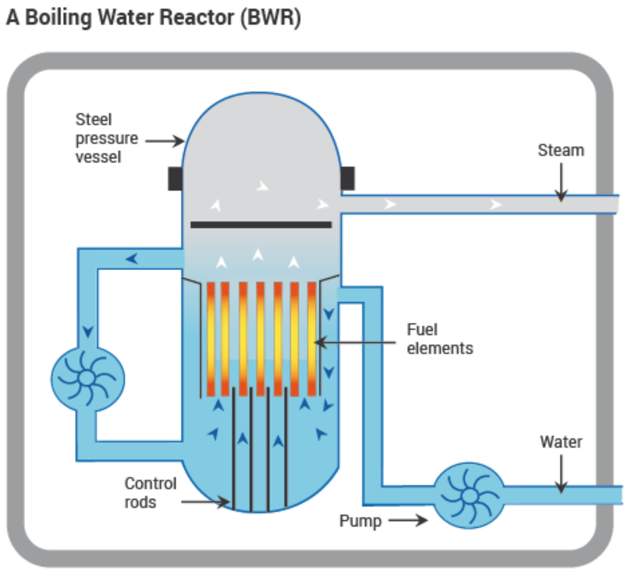


Fig – 3: Boiling Water Reactor[6]

5.3 Pressurized Heavy Water Reactor (PHWR)

Also known as CANDU, generally use natural uranium oxide (0.7% U-235) as fuel, and D_2O is used as moderator. PHWR produces more energy per Kg of mined uranium than other designs. Moderator is in the large tank called a **Calandria**, penetrated by several hundred horizontal pressure tubes which form channels for fuel, cooled by flow of D_2O under high pressure around 100 atms. in primary cooling circuit, typically 290°C. Pressure tubes design means that the reactor can be refuelled without shutting down, by isolation individual pressure tubes from cooling circuit. Fuel assembly of CANDU consist of a bundle of 37 half meter long fuel rods (ceramic fuel pellets in zircaloy tubes) with 12 bundles lying end to end in a support structure of fuel channel. [3]. Control rods penetrated the calandria vertically, and secondary system shutdown involves adding gadolinium to the moderator. CANDU reactor may be operated on recycled uranium from reprocessing LWRs used fuel or blend of this and depleted uranium left over from enrichment plants. Or thorium may also be used in fuel. [6]

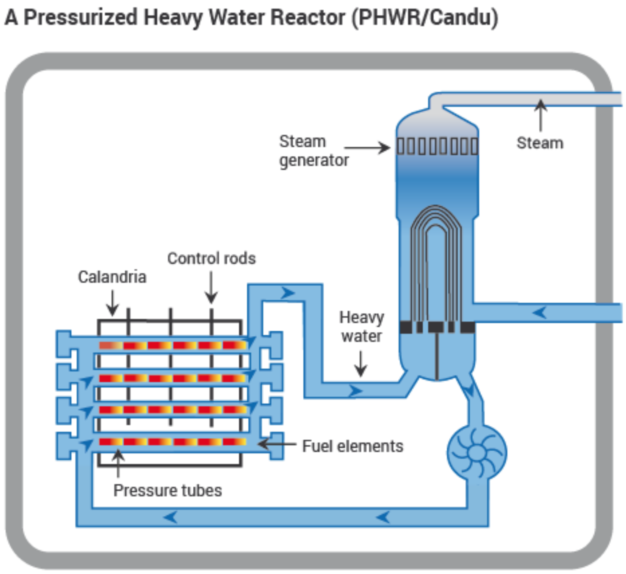
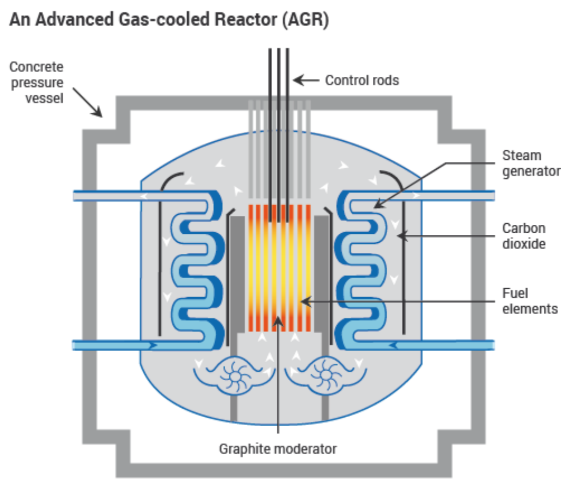


Fig – 4: Pressurized Heavy Water Reactor[6]

5.4 Advance Gas-cooled Reactor (AGR)

AGRs are 2nd generation of British gas cooled reactors, using graphite moderator and CO_2 as primary coolant. The fuel is uranium oxide pellets enriched to 2.5-3.5%, in stainless steel tubes and CO_2 circulates through the core and reaching to 650^{O}C, then past steam generator tubes outside it, but still inside the concrete and steel vessel which is an integral design. Control rods penetrate the moderator and a secondary shutdown system involves injecting Nitrogen to the coolant. AGRs give thermal efficiency about 41% because of high temperature. This design was developed from the Magnox reactor, which were also graphite moderated and CO_2 cooled, used natural uranium fuel in metal form and water as secondary coolant. [7]

Fig-5: Advanced Gas-cooled reactor[6]



5.5 Light Water Graphite-moderated Reactor (LWGR)

LWGRs are also known as RBMK reactor, a Soviet design, developed from plutonium production reactors. It contains 7mtrs long vertical pressure tubes running through graphic moderator and uses water as coolant, which is allowed to boil in the core at 290^{O}C and at 6.9MPa. Fuel is low enriched uranium oxide made up into fuel assemblies 3.5mtrs long. Due to fixed graphite excess moderation is there, and excess boiling reduces the cooling and neutron absorption without inhibiting the fission reaction from which, positive feedback problem may arise. [6]

5.6 Fast Neutron Reactor (FNR)

FNRs generate power from plutonium while making more of it from U-238 isotope. Natural uranium contains about 0.7% U-235 and 93% U-238. [4]. In any reactor some of U-238 component is turned into several isotopes of plutonium during operation, two of these, Pu-239 and Pu-241, then undergo fission in the same way as U-235. FNR uses this process to 'breeds' fuel. Some U-235 is burned directly with neutron energies above 1MeV, so FNRs can utilise uranium about 60% more efficiently. FNR does not uses any moderator and relies on fast neutrons to cause fission for which it uses plutonium as fuel because it fissions sufficiently with fast neutrons. at same time the number of neutrons produces per Pu-239 fission is 25% more than from uranium, and these extra neutrons converts U-238 to Pu-239. Coolant is a liquid metal (usually sodium) to avoid neutron moderation and provide a very efficient heat transfer medium. The ratio of new fissile nuclei to fissioned nuclei in a normal reactor is 0.6, while FNR may exceed 1.0. [7]

6. CONCLUSIONS

For many environmentalists concerned with global warming, nuclear energy is today's 'devil's excrement'. Nuclear power can be one major component of our rescue from a hotter, more meteorologically destructive world. Since it generates base-load electricity with no output of carbon, the major responsible element of global warming. In this paper, each process and component, involved in nuclear reactor is explained.

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BIOGRAPHIES

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