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Comparative Study of Thermal Nuclear Reactors

دراسة مقارنة بين المفاعلات النووية الحرارية

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الآية

قال تعالي :

(وجعلنا من الماء كل شيء حي)

سورة الانبياء الاية ٣٠

DEDICATION

Idedicate this research to reason for my existence and my smile

My parents,

to my husband and companion my life

Saif,

to light of my eyes and my sun that light my way

Njeeb,and

To stood beside me and helped me all my senses were, my sister, I can't got here without you

Islam .

ACKNOWLEDGMENT

It is my pleasure to acknowledge my University Sudan University Science Technology , my supervisor D. Ahmed AL-hassan AL-faki and D.Rasha Abd -Alhay Mohamed Taha , who has support me in all parts of this project so I want to give him all my particularly gratitude for the all thoughtful comments and helpful suggestions .

This contributed so much to the production and quality of the final manuscript.

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ABSTRACT

In this research the thermal reactors have been studied, we reviewed the history of thermal reactors focusing on comparing advantages and disadvantages of using of each thermal reactors class, accordingly to these classification.

we choose the pressure water reactor as the best candidate of these thermal reactors, this is due to the isolations of the second vapor cycle from the pressure and vapor system in the first cycle. This enable the pressure water reactors to be the most stable reactors that produce a low energy with increase in temperature.

الخلاصة

في هذا البحث تم دراسة المفاعلات الحرارية ومن دراسة تاريخ المفاعلات الحرارية ركزنا على مقارنة بين مميزات وعيوب وإستخدامات كل نوع من أنواع المفاعلات الحرارية وتصنيفها.

إخترنا مفاعل الماء المضغوط كأفضل مفاعل بين المفاعلات الحرارية لانفصال حلقة البخار الثانية من ضغط وبخار النظام في الحلقة الأولية ، يعتبر مفاعل الماء المضغوط أكثر استقراراً لميله لإنتاج طاقة أقل عند زيادة درجة الحرارة.

TABLE OF CONTENTS

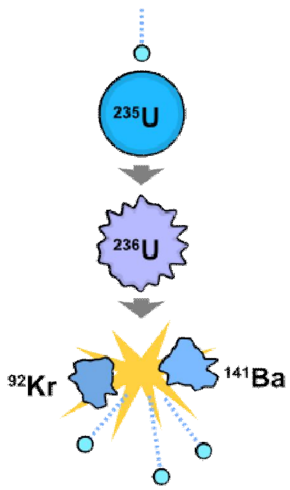
LIST OF FIUGURES

CHPTER ONE

FOREWORD

1.1 Introduction

"Splitting the atom" redirects here. For the EP, see Splitting the Atom as shown in fig (1.1) .



Figure(1.1): splitting the atom

In nuclear physics and nuclear chemistry, nuclear fission is either a nuclear reaction or a radioactive decay process in which the nucleus of an atom splits into smaller parts (lighter nuclei). The fission process often produces free neutrons and photons (in the form of gamma rays), and releases a very large amount of energy even by the energetic standards of radioactive decay.

Nuclear fission of heavy elements was discovered on December 17, 1938 by German Otto Hahn and his assistant Fritz Stresemann, and explained theoretically in January 1939 by Lise Meitner and her nephew Otto Robert Frisch. Frisch named the process by analogy with biological of living cells. It is an exothermic reaction which can release large amounts of energy both as radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). In order for fission to produce energy, the total binding of the resulting elements must be less negative (higher energy) than that of the starting element.

Fission is a form of nuclear transmutation because the resulting fragments are not the same element as the original atom. The two nuclei produced are most often of comparable but slightly different sizes, typically with a mass ratio of products of about 3 to 2, for common fissile isotopes[1][2]. Most fissions are binary fissions (producing two charged fragments), but occasionally (2 to 4 times per 1000 events), *three* positively charged fragments are produced, in a ternary fission. The smallest of these fragments in ternary processes ranges in size from a proton to an argon nucleus.

Fission as encountered in the modern world is usually a deliberately produced man-made nuclear reaction induced by a neutron. It is less commonly encountered as a natural form of spontaneous radioactive decay (not requiring a neutron), occurring especially in very high-mass-number isotopes. The unpredictable composition of the products (which vary in a broad probabilistic and somewhat chaotic manner) distinguishes fission from purely quantum-tunneling processes such as proton emission, alpha decay and cluster decay, which give the same products each time. Nuclear fission produces energy for nuclear power and drives the explosion of nuclear weapons. Both uses are possible because certain substances called nuclear fuels undergo fission when struck by fission neutrons, and in turn emit neutrons when they break apart. This makes possible a self-sustaining nuclear chain reaction that releases energy at a controlled rate in a reactor or at a very rapid uncontrolled rate in a nuclear weapon.

The amount of free energy contained in nuclear fuel is millions of times the amount of free energy contained in a similar mass of chemical fuel such as gasoline, making nuclear fission a very dense source of energy. The products of nuclear fission, however, are on average far more radioactive than the heavy elements which are normally fissioned as fuel, and remain so for significant amounts of time, giving rise to a nuclear waste problem. Concerns over nuclear waste accumulation and over the destructive potential of nuclear weapons may counterbalance the desirable qualities of fission as an energy source, and give rise to ongoing political debate over nuclear power.

1.2 Research significance

Target of this research was differentiation thermal reactor and selection a better thermal reactor commensurate with needed energy and fits our requirements.

1.3 Methodology

In this research method used the Trade-off between the types of kinetic water reactors in terms of energy and fuel used and the basic installation and study disadvantages and advantages of each type out.

1.4 Layout of the research

The research deal with the nuclear reactor and their much part .The research is in two chapters, chapter one is brief general introduction of the nuclear interaction, components of nuclear reactors, classification and enrichment uranium .

The third chapter handled thermal reactors such as (light-water reactors, which are classified into pressurized water reactor and boiling water reactor and reactor water supercritical) , heavy water reactors .

The problem in the research was not possible to do practical research .

CHAPTER TWO

FISSION REACTORS

2.1 Physical overview

2.1.1 Mechanism

In fig (2.1) A visual representation of an induced nuclear fission event where a slow-moving neutron is absorbed by the nucleus of a uranium-235 atom, which fissions into two fast-moving lighter elements (fission products) and additional neutrons. Most of the energy released is in the form of the kinetic velocities of the fission products and the neutrons .

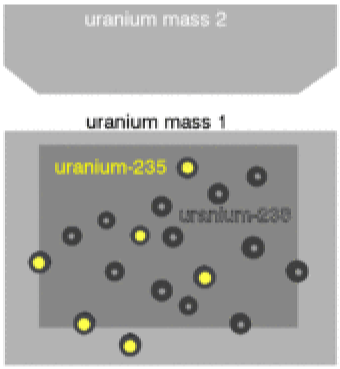


Figure (2.1): Uranium mass

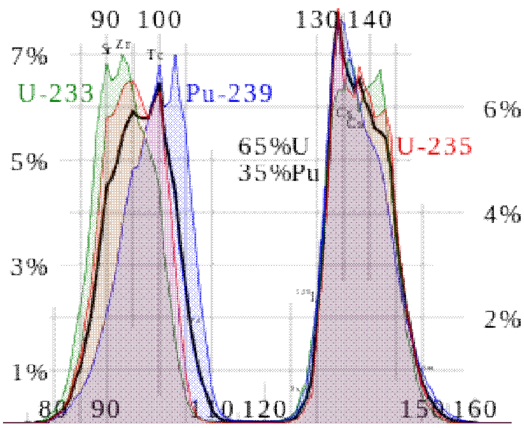


Figure (2.2) : Fission product yields by mass for thermal neutron fission

In fig (2.2) Fission product yields by mass for thermal neutron fission of U-235, Pu-239, a combination of the two typical of current nuclear power reactors, and U-233used in the thorium cycle [3].

Nuclear fission can occur without neutron bombardment as a type of radioactive decay. This type of fission (called spontaneous fission) is rare except in a few heavy isotopes. In engineered nuclear devices, essentially all nuclear fission occurs as a "nuclear reaction" — a bombardment-driven process that results from the collision of two subatomic particles. In nuclear reactions, a subatomic particle collides with an atomic nucleus and causes changes to it. Nuclear reactions are thus driven by the mechanics of bombardment, not by the relatively constant exponential decay and half-life characteristic of spontaneous radioactive processes.

Many types of nuclear reactions are currently known. Nuclear fission differs importantly from other types of nuclear reactions, in that it can be amplified and sometimes controlled via a nuclear chain reaction (one type of general chain reaction). In such a reaction, free neutrons released by each fission event can trigger yet more events, which in turn release more neutrons and cause more fissions.

The chemical element isotopes that can sustain a fission chain reaction are called nuclear fuels, and are said to be *fissile*. The most common nuclear fuels are ^{235}U (the isotope of uranium with an atomic mass of 235 and of use in nuclear reactors) and ^{239}Pu (the isotope of plutonium with an atomic mass of 239). These fuels break apart into a bimodal range of chemical elements with atomic masses centering near 95 and 135 u (fission products). Most nuclear fuels undergo spontaneous fission only very slowly, decaying instead mainly via an alpha/beta decay chain over periods of millennia to eons. In a nuclear reactor or nuclear weapon, the overwhelming majority of fission events are induced by bombardment with another particle, a neutron, which is itself produced by prior fission events.

Nuclear fissions in fissile fuels are the result of the nuclear excitation energy produced when a fissile nucleus captures a neutron. This energy, resulting from the neutron capture, is a result of the attractive nuclear force acting between the neutron and nucleus. It is enough to deform the nucleus into a double-lobed "drop," to the point that nuclear fragments exceed the distances at which the nuclear force can hold two groups of charged nucleons together, and when this happens, the two fragments complete their separation and then are driven further apart by their mutually repulsive charges, in a process which becomes irreversible with greater and greater distance. A similar process occurs in fissionable isotopes (such as uranium-238), but in order to fission, these isotopes require additional energy provided by fast neutrons (such as those produced by nuclear fusion in thermonuclear).

The liquid drop model of the atomic nucleus predicts equal-sized fission products as an outcome of nuclear deformation. The more sophisticated nuclear shell model is needed to mechanistically explain the route to the more energetically favorable outcome, in which one fission product is slightly smaller than the other. A theory of the fission based on shell model has been formulated by Maria Gosper Mayer [3] .

The most common fission process is binary fission.

2.1.2 Energetic

2.1.2.1 Input

Energy input deforms the nucleus into a fat "cigar" shape, then a "peanut" shape, followed by binary fission as the two lobes exceed the short-range strong force attraction distance, then are pushed apart and away by their electrical charge. In the liquid drop model, the two fission fragments are predicted to be the same size. The nuclear shell model allows for them to differ in size, as usually experimentally observed as shown in fig (2.3) .

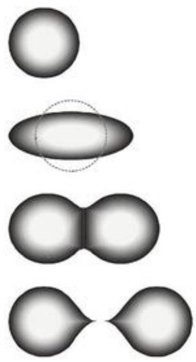


Figure (2.3) : The stages of binary fission in a liquid drop model

The fission of a heavy nucleus requires a total input energy of about 7 to 8 million electron volts (MeV) to initially overcome the strong force which holds the nucleus into a spherical or nearly spherical shape, and from there, deform it into a two-lobed ("peanut") shape in which the lobes are able to continue to separate from each other, pushed by their mutual positive charge, in the most common process of binary fission (two positively charged fission products + neutrons). Once the nuclear lobes have been pushed to a critical distance, beyond which the short range strong force can no longer hold them together, the process of their separation proceeds from the energy of the (longer range) electromagnetic repulsion between the fragments. The result is two fission fragments moving away from each other, at high energy [4].

About 6 MeV of the fission-input energy is supplied by the simple binding of an extra neutron to the heavy nucleus via the strong force; however, in many fissionable isotopes, this amount of energy is not enough for fission. Uranium-238, for example, has a near-zero fission cross section for neutrons of less than one MeV energy. If no additional energy is supplied by any other mechanism, the nucleus will not fission, but will merely absorb the neutron, as happens when U-238 absorbs slow and even some fraction of fast neutrons, to become U-239. The remaining energy to initiate fission can be supplied by two other mechanisms: one of these is more kinetic energy of the incoming neutron, which is increasingly able to fission a fissionable heavy nucleus as it exceeds a kinetic energy of one MeV or more (so-called fast neutrons). Such high energy neutrons are able to fission U-238 directly (see thermonuclear weapon for application, where the fast neutrons are supplied by nuclear fusion). However, this process cannot happen to a great extent in a nuclear reactor, as too small a fraction of the fission neutrons produced by any type of fission have enough energy to efficiently fission U-238 (fission neutrons have a mode energy of 2 MeV, but a median of only 0.75 MeV, meaning half of them have less than this insufficient energy) [4]

Among the heavy actinide elements, however, those isotopes that have an odd number of neutrons (such as U-235 with 143 neutrons) bind an extra neutron with an additional 1 to 2 MeV of energy over an isotope of the same element with an even number of neutrons (such as U-238 with 146 neutrons). This extra binding energy is made available as a result of the mechanism of neutron pairing effects. This extra energy results from the Pauli exclusion principle allowing an extra neutron to occupy the same nuclear orbital as the last neutron in the nucleus, so that the two form a pair. In such isotopes, therefore, no neutron kinetic energy is needed, for all the necessary energy is supplied by absorption of any neutron, either of the slow or fast variety (the former are used in moderated nuclear reactors, and the latter are used in fast neutron reactors, and in weapons). As noted above, the subgroup of fissionable elements that may be fissioned efficiently with their own fission neutrons (thus potentially causing a nuclear reaction in relatively small amounts of the pure material) are termed "fissile." Examples of fissile isotopes are U-235 and plutonium-239.

2.1.2.2 Output

Typical fission events release about two hundred million eV (200 MeV) of energy for each fission event. The exact isotope which is fashioned, and whether or not it is fissionable or fissile, has only a small impact on the amount of energy released. This can be easily seen by examining the curve of binding (image below), and noting that the average binding energy of the actinide nuclides beginning with uranium is around 7.6 MeV per nucleon. Looking further left on the curve of binding energy, where the fission products cluster, it is easily observed that the binding energy of the fission products tends to center around 8.5 MeV per nucleon. Thus, in any fission event of an isotope in the actinide's range of mass, roughly 0.9 MeV is released per nucleon of the starting element. The fission of U235 by a slow neutron yields nearly identical energy to the fission of U238 by a fast neutron. This energy release profile holds true for thorium and the various minor actinides as well [5] .

By contrast, most chemical oxidation reactions (such as burning coal or TNT) release at most a few eV per event. So, nuclear fuel contains at least ten million times more usable energy per unit mass than does chemical fuel. The energy of nuclear fission is released as kinetic energy of the fission products and fragments, and as radiation in the form of gamma rays; in a nuclear reactor, the energy is converted to heat as the particles and gamma rays collide with the atoms that make up the reactor and its working fluid, usually water or occasionally heavy water or molten salts.

When a uranium nucleus fissions into two daughter nuclei fragments, about 0.1 percent of the mass of the uranium nucleus[6]. appears as the fission energy of ~200 MeV. For uranium-235 (total mean fission energy 202.5 MeV), typically ~169 MeV appears as the kinetic energy of the daughter nuclei, which fly apart at about 3% of the speed of light, due to Coulomb repulsion. Also, an average of 2.5 neutrons are emitted, with a mean kinetic energy per neutron of ~2 MeV (total of 4.8 MeV) [7] The fission reaction also releases ~7 MeV in prompt gamma ray photons. The latter figure means that a nuclear fission explosion or criticality accident emits about 3.5% of its energy as gamma rays, less than 2.5% of its energy as fast neutrons (total of both types of radiation ~ 6%), and the rest as kinetic energy of fission fragments (this appears almost immediately when the fragments impact surrounding matter, as simple heat). In an atomic bomb, this heat may serve to raise the temperature of the bomb core to 100 million Kelvin and cause secondary emission of soft X-rays, which convert some of this energy to ionizing radiation. However, in nuclear reactors, the fission fragment kinetic energy remains as low-temperature heat, which itself causes little or no ionization.

So-called neutron bombs (enhanced radiation weapons) have been constructed which release a larger fraction of their energy as ionizing radiation (specifically, neutrons), but these are all thermonuclear devices which rely on the nuclear fusion stage to produce the extra radiation. The energy dynamics of pure fission bombs always remain at about 6% yield of the total in radiation, as a prompt result of fission.

The total prompt fission energy amounts to about 181 MeV, or ~ 89% of the total energy which is eventually released by fission over time. The remaining ~ 11% is released in beta decays which have various half-lives, but begin as a process in the fission products immediately; and in delayed gamma emissions associated with these beta decays. For example, in uranium-235 this delayed energy is divided into about 6.5 MeV in betas, 8.8 MeV in antineutrinos (released at the same time as the betas), and finally, an additional 6.3 MeV in delayed gamma emission from the excited beta-decay products (for a mean total of ~10 gamma ray emissions per fission, in all). Thus, about 6.5% of the total energy of fission is released some time after the event, as non-prompt or delayed ionizing radiation, and the delayed ionizing energy is about evenly divided between gamma and beta ray energy.

In a reactor that has been operating for some time, the radioactive fission products will have built up to steady state concentrations such that their rate of decay is equal to their rate of formation, so that their fractional total contribution to reactor heat (via beta decay) is the same as these radioisotopic fractional contributions to the energy of fission. Under these conditions, the 6.5% of fission which appears as delayed ionizing radiation (delayed gammas and betas from radioactive fission products) contributes to the steady-state reactor heat production under power. It is this output fraction which remains when the reactor is suddenly shut down (undergoes scram). For this reason, the reactor decay heatoutput begins at 6.5% of the full reactor steady state fission power, once the reactor is shut down. However, within hours, due to decay of these isotopes, the decay power output is far less. See decay heat for detail.

The remainder of the delayed energy (8.8 MeV/202.5 MeV = 4.3% of total fission energy) is emitted as antineutrinos, which as a practical matter, are not considered "ionizing radiation." The reason is that energy released as antineutrinos is not captured by the reactor material as heat, and escapes directly through all materials (including the Earth) at nearly the speed of light, and into interplanetary space (the amount absorbed is minuscule). Neutrino radiation is ordinarily not classed as ionizing radiation, because it is almost entirely not absorbed and therefore does not produce effects (although the very rare neutrino event is ionizing). Almost all of the rest of the radiation (6.5% delayed beta and gamma radiation) is eventually converted to heat in a reactor core or its shielding.

Some processes involving neutrons are notable for absorbing or finally yielding energy — for example neutron kinetic energy does not yield heat immediately if the neutron is captured by a uranium-238 atom to breed plutonium-239, but this energy is emitted if the plutonium-239 is later fissioned. On the other hand, so-called delayed neutrons emitted as radioactive decay products with half-lives up to several minutes, from fission-daughters, are very important to reactor control, because they give a characteristic "reaction" time for the total nuclear reaction to double in size, if the reaction is run in a "delayed-critical" zone which deliberately relies on these neutrons for a supercritical chain-reaction (one in which each fission cycle yields more neutrons than it absorbs). Without their existence, the nuclear chain-reaction would be prompt critical and increase in size faster than it could be controlled by human intervention. In this case, the first experimental atomic reactors would have run away to a dangerous and messy "prompt critical reaction" before their operators could have manually shut them down (for this reason, designer Enrico Fermi included radiation-counter-triggered control rods, suspended by electromagnets, which could automatically drop into the center of Chicago Pile-1). If these delayed neutrons are captured without producing fissions, they produce heat as well [8].

2.2 Product nuclei and binding energy

In fission there is a preference to yield fragments with even proton numbers, which is called the odd-even effect on the fragments charge distribution. However, no odd-even effect is observed on fragment mass number distribution. This result is attributed to nucleon pair breaking.

In nuclear fission events the nuclei may break into any combination of lighter nuclei, but the most common event is not fission to equal mass nuclei of about mass 120; the most common event (depending on isotope and process) is a slightly unequal fission in which one daughter nucleus has a mass of about 90 to 100 u and the other the remaining 130 to 140 u[9]. Unequal fissions are energetically more favorable because this allows one product to be closer to the energetic minimum near mass 60 u (only a quarter of the average fissionable mass), while the other nucleus with mass 135 u is still not far out of the range of the most tightly bound nuclei (another statement of this, is that the atomic binding curve is slightly steeper to the left of mass 120 u than to the right of it).

Origin of the active energy and the curve of binding energy

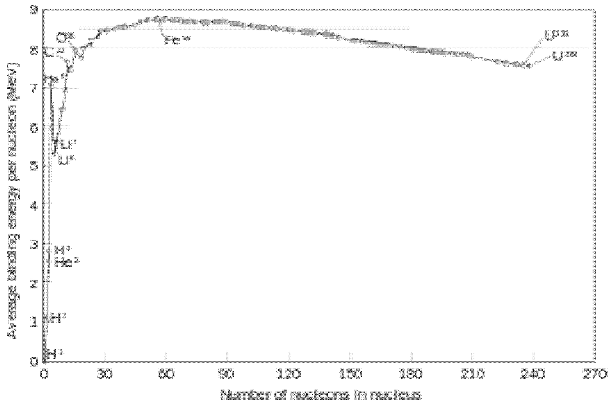


Figure (2.4) : The "curve of binding energy"

In fig (2.4) shown The "curve of binding energy": A graph of binding energy per nucleon of common isotopes.uclear fission of heavy elements produces energy because the specific binding energy (binding energy per mass) of intermediate-mass nuclei with atomic numbers and atomic masses close to ^{62}Ni and ^{56}Fe is greater than the nucleon-specific binding energy of very heavy nuclei, so that energy is released when heavy nuclei are broken apart. The total rest masses of the fission products (Mp) from a single reaction is less than the mass of the original fuel nucleus (M). The excess mass $\Delta m = M - Mp$ is the invariant mass of the energy that is released as photons (gamma rays) and kinetic energy of the fission fragments, according to the mass-energy equivalence formula $E = mc^2$.

The variation in specific binding energy with atomic number is due to the interplay of the two fundamental forces acting on the component nucleons (protons and neutrons) that make up the nucleus. Nuclei are bound by an attractive nuclear force between nucleons, which overcomes the electrostatic repulsion between protons. However, the nuclear force acts only over relatively short ranges (a few nucleon diameters), since it follows an exponentially decaying Yukawa potential which makes it insignificant at longer distances. The electrostatic repulsion is of longer range, since it decays by an inverse-square rule, so that nuclei larger than about 12 nucleons in diameter reach a point that the total electrostatic repulsion overcomes the nuclear force and causes them to be spontaneously unstable. For the same reason, larger nuclei (more than about eight nucleons in diameter) are less tightly bound per unit mass than are smaller nuclei; breaking a large nucleus into two or more intermediate-sized nuclei releases energy. The origin of this energy is the nuclear force, which intermediate-sized nuclei allows to act more efficiently, because each nucleon has more neighbors which are within the short range attraction of this force. Thus less energy is needed in the smaller nuclei and the difference to the state before is set free.

Also because of the short range of the strong binding force, large stable nuclei must contain proportionally more neutrons than do the lightest elements, which are most stable with a 1 to 1 ratio of protons and neutrons. Nuclei which have more than 20 protons cannot be stable unless they have more than an equal number of neutrons. Extra neutrons stabilize heavy elements because they add to strong-force binding (which acts between all nucleons) without adding to proton–proton repulsion. Fission products have, on average, about the same ratio of neutrons and protons as their parent nucleus, and are therefore usually unstable to beta decay (which changes neutrons to protons) because they have proportionally too many neutrons compared to stable isotopes of similar mass.

This tendency for fission product nuclei to beta-decay is the fundamental cause of the problem of radioactive high level waste from nuclear reactors. Fission products tend to bebeta emitters, emitting fast-moving electrons to conserve electric charge, as excess neutrons convert to protons in the fission-product atoms. See Fission products (by element)for a description of fission products sorted by element [7].

2.3Chain reactions

Auranium-235 atom absorbs a neutron and fissions into two new atoms (fission fragments), releasing three new neutrons and some binding energy. 2. One of those neutrons is absorbed by an atom of uranium-238 and does not continue the reaction. Another neutron is simply lost and does not collide with anything, also not continuing the reaction. However, one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and some binding energy. 3. Both of those neutrons collide with uranium-235 atoms, each of which fissions and releases between one and three neutrons, which can then continue the reaction as shown in fig (2.5).

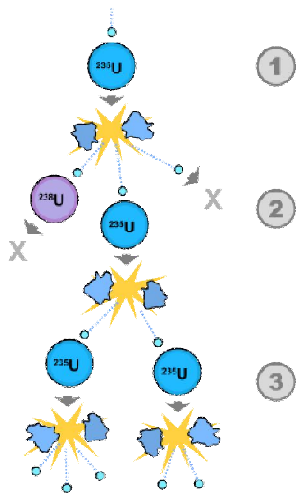


Figure (2.5) : A schematic nuclear fission chain reaction.

Several heavy elements, such as uranium, thorium, and plutonium, undergo both spontaneous fission, a form of radioactive decay and induced fission, a form of nuclear reaction. Elemental isotopes that undergo induced fission when struck by a free neutron are called fissionable; isotopes that undergo fission when struck by a thermal, slow moving neutron are also called fissile. A few particularly fissile and readily obtainable isotopes (notably ^{233}U, ^{235}U and ^{239}Pu) are called nuclear fuels because they can sustain a chain reaction and can be obtained in large enough quantities to be useful [7].

All fissionable and fissile isotopes undergo a small amount of spontaneous fission which releases a few free neutrons into any sample of nuclear fuel. Such neutrons would escape rapidly from the fuel and become a free neutron, with a mean lifetime of about 15 minutes before decaying to protons and beta particles. However, neutrons almost invariably impact and are absorbed by other nuclei in the vicinity long before this happens (newly created fission neutrons move at about 7% of the speed of light, and even moderated neutrons move at about 8 times the speed of sound). Some neutrons will impact fuel nuclei and induce further fissions, releasing yet more neutrons. If enough nuclear fuel is assembled in one place, or if the escaping neutrons are sufficiently contained, then these freshly emitted neutrons outnumber the neutrons that escape from the assembly, and a sustained nuclear chain reaction will take place.

An assembly that supports a sustained nuclear chain reaction is called a critical assembly or, if the assembly is almost entirely made of a nuclear fuel, a critical mass. The word "critical" refers to a cusp in the behavior of the differential equation that governs the number of free neutrons present in the fuel: if less than a critical mass is present, then the amount of neutrons is determined by radioactive decay, but if a critical mass or more is present, then the amount of neutrons is controlled instead by the physics of the chain reaction. The actual mass of a critical mass of nuclear fuel depends strongly on the geometry and surrounding materials.

Not all fissionable isotopes can sustain a chain reaction. For example, ^{238}U, the most abundant form of uranium, is fissionable but not fissile: it undergoes induced fission when impacted by an energetic neutron with over 1 MeV of kinetic energy. However, too few of the neutrons produced by ^{238}U fission are energetic enough to induce further fissions in ^{238}U, so no chain reaction is possible with this isotope. Instead, bombarding ^{238}U with slow neutrons causes it to absorb them (becoming ^{239}U) and decay by beta emission to ^{239}Np which then decays again by the same process to ^{239}Pu; that process is used to manufacture ^{239}Pu in breeder reactors. In-situ plutonium production also contributes to the neutron chain reaction in other types of reactors after sufficient plutonium-239 has been produced, since plutonium-239 is also a fissile element which serves as fuel. It is estimated that up to half of the power produced by a standard "non-breeder" reactor is produced by the fission of plutonium-239 produced in place, over the total life-cycle of a fuel load [7].

Fissionable, non-fissile isotopes can be used as fission energy source even without a chain reaction. Bombarding ^{238}U with fast neutrons induces fissions, releasing energy as long as the external neutron source is present. This is an important effect in all reactors where fast neutrons from the fissile isotope can cause the fission of nearby ^{238}U nuclei, which means that some small part of the ^{238}U is "burned-up" in all nuclear fuels, especially in fast breeder reactors that operate with higher-energy neutrons. That same fast-fission effect is used to augment the energy released by modern thermonuclear weapons, by jacketing the weapon with ^{238}U to react with neutrons released by nuclear fusion at the center of the device. But the explosive effects of nuclear fission chain reactions can be reduced by using substances like moderators which slow down the speed of secondary neutrons.

2.4 Fission reactors

Critical fission reactors are the most common type of nuclear reactor. In a critical fission reactor, neutrons produced by fission of fuel atoms are used to induce yet more fissions, to sustain a controllable amount of energy release. Devices that produce engineered but non-self-sustaining fission reactions are subcritical fission reactors. Such devices use radioactive decay or particle accelerators to trigger fissions.

Critical fission reactors are built for three primary purposes, which typically involve different engineering trade-offs to take advantage of either the heat or the neutrons produced by the fission chain reaction:

- power reactors are intended to produce heat for nuclear power, either as part of a generating station or a local power system such as a nuclear.
- research reactors are intended to produce neutrons and/or activate radioactive sources for scientific, medical, engineering, or other research purposes.
- breeder reactors are intended to produce nuclear fuels in bulk from more abundant isotopes. The better known fast breeder reactor makes ^{239}Pu (a nuclear fuel) from the naturally very abundant ^{238}U (not a nuclear fuel). Thermal breeder reactors previously tested using ^{232}Th to breed the fissile isotope ^{233}U (thorium fuel cycle) continue to be studied and developed.

While, in principle, all fission reactors can act in all three capacities, in practice the tasks lead to conflicting engineering goals and most reactors have been built with only one of the above tasks in mind. (There are several early counter-examples, such as the Hanford N reactor, now decommissioned). Power reactors generally convert the kinetic energy of fission products into heat, which is used to heat a working fluid and drive a heat engine that generates mechanical or electrical power. The working fluid is usually water with a steam turbine, but some designs use other materials such as gaseous helium. Research reactors produce neutrons that are used in various ways, with the heat of fission being treated as an unavoidable waste product. Breeder reactors are a specialized form of research reactor, with the caveat that the sample being irradiated is usually the fuel itself, a mixture of ^{238}U and ^{235}U. For a more detailed description of the physics and operating principles of critical fission reactors, see nuclear reactor physics. For a description of their social, political, and environmental aspects, see nuclear power [7].

2.5 Components

The key components common to most types of nuclear power plants are:

- Nuclear fuel
- Nuclear reactor core
- Neutron moderator
- Neutron poison
- Neutron howitzer (provides steady source of neutrons to re-initiate reaction following shutdown)
- Coolant (often the Neutron Moderator and the Coolant are the same, usually both purified water)
- Control rods
- Reactor vessel
- Boiler feedwater pump
- Steam generators (not in BWRs)
- Steam turbine
- Electrical generator
- Condenser
- Cooling tower (not always required)
- Radwaste System (a section of the plant handling radioactive waste)
- Refueling Floor
- Spent fuel pool
- Nuclear safety systems
- Reactor Protective System (RPS)
- Emergency Diesel Generators
- Emergency Core Cooling Systems (ECCS)
- Standby Liquid Control System (emergency boron injection, in BWRs only)
- Essential service water system (ESWS)
- Containment building
- Control room
- Emergency Operations Facility
- Nuclear training facility (usually contains a Control Room simulator)[7].

2.6 Reactor types

2.6.1 Classifications

Nuclear Reactors are classified by several methods; a brief outline of these classification methods is provided.

2.6.1.1 Classification by type of nuclear reaction

- Nuclear fission. All commercial power reactors are based on nuclear fission. They generally use uranium and its product plutonium as nuclear, though a thorium fuel cycle is also possible. Fission reactors can be divided roughly into two classes, depending on the energy of the neutrons that sustain the fission chain reaction:
  - Thermal reactors (the most common type of nuclear reactor) use slowed or thermal neutrons to keep up the fission of their fuel. Almost all current reactors are of this type. These contain neutron moderator materials that slow neutrons until their neutron temperature is thermalized, that is, until their kinetic energy approaches the average kinetic energy of the surrounding particles. Thermal neutrons have a far higher cross-section (probability) of fashioning the fissile nuclei uranium-235, plutonium-239, andplutonium-241, and a relatively lower probability of neutron capture by uranium-238 (U-238) compared to the faster neutrons that originally result from fission, allowing use of low-enriched uranium or even natural uranium fuel. The moderator is often also the coolant, usually water under high pressure to increase the boiling point. These are surrounded by a reactor vessel, instrumentation to monitor and control the reactor, radiation shielding, and a containment building.
  - Fast neutron reactors use fast neutrons to cause fission in their fuel. They do not have a neutron moderator, and use less-moderating coolants. Maintaining a chain reaction requires the fuel to be more highly enriched in fissile material (about 20% or more) due to the relatively lower probability of fission versus capture by U-238. Fast reactors have the potential to produce lesstransuranic waste because all actinides are fissionable with fast neutrons,[19] but they are more difficult to build and more expensive to operate. Overall, fast reactors are less common than thermal reactors in most applications. Some early power stations were fast reactors, as are some Russian naval propulsion units. Construction of prototypes is continuing (see fast breeder or generation IV reactors) [7].
- Nuclear fusion. Fusion power is an experimental technology, generally with hydrogen as fuel. While not suitable for power production, Farnsworth-Hirsch fusors are used to produce neutron radiation.

2.6.1.2 Classification by moderator material Used by thermal reactors:

- Graphite-moderated reactors
- Water moderated reactors
    - Heavy-water reactors (Used in Canada.)
    - Light-water-moderated reactors (LWRs). Light-water reactors (the most common type of thermal reactor) use ordinary water to moderate and cool the reactors. When at operating, if the temperature of the water increases, its density drops, and fewer neutrons passing through it are slowed enough to trigger further reactions. That negative feedback stabilizes the reaction rate. Graphite and heavy-water reactors tend to be more thoroughly thermalized than light water reactors. Due to the extra thermalization, these types can use natural uranium/unenriched fuel.
- Light-element-moderated reactors. These reactors are moderated by lithium or beryllium.
    - Molten salt reactors (MSRs) are moderated by a light elements such as lithium or beryllium, which are constituents of the coolant/fuel matrix salts LiF and BeF_2.
    - Liquid metal cooled reactors, such as one whose coolant is a mixture of lead and bismuth, may use BeO as a moderator.
- Organically moderated reactors (OMR) use biphenyl and terphenyl as moderator and coolant.

2.6.1.3 Classification by coolant

- Water cooled reactor. There are 104 operating reactors in the United States. Of these, 69 are pressurized water reactors (PWR), and 35 are boiling water reactors (BWR).
- Pressurized water reactor (PWR) Pressurized water reactors constitute the large majority of all Western nuclear power plants.
    - A primary characteristic of PWRs is a pressurizer, a specialized pressure vessel. Most commercial PWRs and naval reactors use pressurizers. During normal operation, a pressurizer is partially filled with water, and a steam bubble is maintained above it by heating the water with submerged heaters. During normal operation, the pressurizer is connected to the primary reactor pressure vessel (RPV) and the pressurizer "bubble" provides an expansion space for changes in water volume in the reactor. This arrangement also provides a means of pressure control for the reactor by increasing or decreasing the steam pressure in the pressurizer using the pressurizer heaters [7].

- Pressurised heavy water reactors are a subset of pressurized water reactors, sharing the use of a pressurized, isolated heat transport loop, but using heavy water as coolant and moderator for the greater neutron economies it offers.

- Boiling water reactor (BWR)
  - BWRs are characterized by boiling water around the fuel rods in the lower portion of a primary reactor pressure vessel. A boiling water reactor uses ^{235}U, enriched as uranium dioxide, as its fuel. The fuel is assembled into rods housed in a steel vessel that is submerged in water. The nuclear fission causes the water to boil, generating steam. This steam flows through pipes into turbines. The turbines are driven by the steam, and this process generates electricity.[22] During normal operation, pressure is controlled by the amount of steam flowing from the reactor pressure vessel to the turbine.
- Pool-type reactor
- Liquid metal cooled reactor. Since water is a moderator, it cannot be used as a coolant in a fast reactor. Liquid metal coolants have included sodium, NaK, lead, lead-bismuth eutectic, and in early reactors, mercury.
- Sodium-cooled fast reactor
- Lead-cooled fast reactor
- Gas cooled reactors are cooled by a circulating inert gas, often helium in high-temperature designs, while carbon dioxide has been used in past British and French nuclear power plants. Nitrogen has also been used.Utilization of the heat varies, depending on the reactor. Some reactors run hot enough that the gas can directly power a gas turbine. Older designs usually run the gas through a heat exchanger to make steam for a steam turbine.
- Molten salt reactors (MSRs) are cooled by circulating a molten salt, typically a eutectic mixture of fluoride salts, such as FLiBe. In a typical MSR, the coolant is also used as a matrix in which the fissile material is dissolved.

2.6.1.4 Classification by generation

- Generation I reactor (early prototypes, research reactors, non-commercial power producing reactors) .
- Generation II reactor (most current nuclear power plants 1965–1996) .
- Generation III reactor (evolutionary improvements of existing designs 1996-now) .
- Generation IV reactor (technologies still under development unknown start date, possibly 2030) [7].

The "Gen IV"-term was dubbed by the United States Department of Energy (DOE) for developing new plant types in 2000. In 2003, the French Commissariat à l' Énergie Atomique (CEA) was the first to refer to Gen II types in Nucleonics Week , first mentioning of Gen III was also in 2000 in conjunction with the launch of the Generation IV International Forum (GIF) plans.

2.6.1.5 Classification by phase of fuel

- Solid fueled
- Fluid fueled
- Aqueous homogeneous reactor
- Molten salt reactor
- Gas fueled (theoretical)

2.6.1.6 Classification by use

- Electricity
- Nuclear power plants including small modular reactors
- Propulsion, see nuclear propulsion
- Nuclear marine propulsion
- Various proposed forms of rocket propulsion
- Other uses of heat
- Desalination
- Heat for domestic and industrial heating
- Hydrogen production for use in a hydrogen economy
- Production reactors for transmutation of elements
- Breeder reactors are capable of producing more fissile material than they consume during the fission chain reaction (by converting fertile U-238 to Pu-239, or Th-232 to U-233). Thus, a uranium breeder reactor, once running, can be re-fueled with natural or even depleted uranium, and a thorium breeder reactor can be re-fueled with thorium; however, an initial stock of fissile material is required
- Creating various radioactive isotopes, such as americium for use in smoke detectors, and cobalt-60, molybdenum-99 and others, used for imaging and medical treatment.
- Production of materials for nuclear weapons such as weapons-grade plutonium
- Providing a source of neutron radiation (for example with the pulsed Godiva device) and positron radiation [7].
- (e.g. neutron activation analysis and potassium-argon dating.
- Research reactor: Typically reactors used) for research and training, materials testing, or the production of radioisotopes for medicine and industry. These are much smaller than power reactors or those

propelling ships, and many are on university campuses. There are about 280 such reactors operating, in 56 countries. Some operate with high-enriched uranium fuel, and international efforts are underway to substitute low-enriched fuel..

2.7 safety

Nuclear safety covers the actions taken to prevent nuclear and radiation accidents or to limit their consequences. The nuclear power industry has improved the safety and performance of reactors, and has proposed new safer (but generally untested) reactor designs but there is no guarantee that the reactors will be designed, built and operated correctly. Mistakes do occur and the designers of reactors at Fukushima in Japan did not anticipate that a tsunami generated by an earthquake would disable the backup systems that were supposed to stabilize the reactor after the earthquake. According to UBS AG, the Fukushima I nuclear accidents have cast doubt on whether even an advanced economy like Japan can master nuclear safety. Catastrophic scenarios involving terrorist attacks are also conceivable. An interdisciplinary team from MIT have estimated that given the expected growth of nuclear power from 2005–2055, at least four serious nuclear accidents would be expected in that period [7].

CHAPTER THREE

LIGHT WATER REACTOR

3.1 The light water reactor

The light water reactor (LWR) is a type of thermal-neutron reactor that uses normal water, as opposed to heavy water, as both its coolant and neutron moderator furthermore a solid form of fissile elements is used as fuel. Thermal-neutron reactors are the most common type of nuclear reactor, and light water reactors are the most common type of thermal-neutron reactor.

There are three varieties of light water reactors: the pressurized water reactor (PWR), the boiling water reactor (BWR), and (most designs of) the supercritical water reactor (SCWR).

3.2 Reactor design

The light water reactor produces heat by controlled nuclear fission. The nuclear reactor core is the portion of a nuclear reactor where the nuclear reactions take place. It mainly consists of nuclear fuel and control elements. The pencil-thin nuclear fuel rods, each about 12 feet (3.7 m) long, are grouped by the hundreds in bundles called fuel assemblies. Inside each fuel rod, pellets of uranium, or more commonly uranium oxide, are stacked end to end. The control elements, called control rods, are filled with pellets of substances like hafnium or cadmium that readily capture neutrons. When the control rods are lowered into the core, they absorb neutrons, which thus cannot take part in the chain reaction. On the converse, when the control rods are lifted out of the way, more neutrons strike the fissile uranium-235 or plutonium-239 nuclei in nearby fuel rods, and the chain reaction intensifies. All of this is enclosed in a water-filled steel pressure vessel, called the reactor vessel.

In the boiling water reactor, the heat generated by fission turns the water into steam, which directly drives the power-generating turbines. But in the pressurized water reactor, the heat generated by fission is transferred to a secondary loop via a heat exchanger. Steam is produced in the secondary loop, and the secondary loop drives the power-generating turbines. In either case, after flowing through the turbines, the steam turns back into water in the condenser [9].

The water required to cool the condenser is taken from a nearby river or ocean. It is then pumped back into the river or ocean, in warmed condition. The heat could also be dissipated via a cooling tower into the atmosphere [10].

3.2.1 Control

A pressurized water reactor head, with the control rods visible on top .control rods are usually combined into control rod assemblies – typically 20 rods for a commercial pressurized water reactor assembly – and inserted into guide tubes within a fuel element. A control rod s removed from or inserted into the central core of a nuclear reactor in order to control the number of neutrons which will split further uranium atoms . this in turn affects the thermal power of the reactor, the amount of steam generates, and hence the electricity produced. The control rods are partially removed from the core to allow a chain reaction to occur . the number of control rods inserted and the distance by which they are inserted can be varied to control the reactivity of the reactor .

Usually there are also other means of controlling reactivity. In the PWR design a soluble neutron absorber, usually boric acid, is added to the reactor coolant allowing the complete extraction of the control rods during stationary power operation ensuring an even power and flux distribution over the entire core. Operators of the BWR design use the coolant flow through the core to control reactivity by varying the speed of the reactor recirculation pumps. An increase in the coolant flow through the core improves the removal of steam bubbles, thus increasing the density of the coolant/moderator with the result of increasing power.

3.2.2 Coolant

The light water reactor also uses ordinary water to keep the reactor cooled. The cooling source, light water, is circulated past the reactor core to absorb the heat that it generates. The heat is carried away from the reactor and is then used to generate steam. Most reactor systems employ a cooling system that is physically separate from the water that will be boiled to produce pressurized steam for the turbines, like the pressurized-water reactor. But in some reactors the water for the steam turbines is boiled directly by the reactor core, for example the boiling-water reactor.

3.2.3 Fuel

The use of ordinary water makes it necessary to do a certain amount of enrichment of the uranium fuel before the necessary criticality of the reactor can be maintained. The light water reactor uses uranium 235 as a fuel, enriched to approximately 3 percent. Although this is its major fuel, the uranium 238 atoms also contribute to the fission process by converting to plutonium 239; about one-half of which is consumed in the reactor. Light-water reactors are generally refueled every 12 to 18 months, at which time, about 25 percent of the fuel is replaced[11] .

Figure (3.1) : A nuclear fuel pellet

The enriched UF_6 is converted into uranium dioxide powder that is then processed into pellet form. The pellets are then fired in a high-temperature, sintering furnace to create hard, ceramic pellets of enriched uranium as shown in fig (3.1). The cylindrical pellets then undergo a grinding process to achieve a uniform pellet size. The uranium oxide is dried before inserting into the tubes to try to eliminate moisture in the ceramic fuel that can lead to corrosion and hydrogen embrittlement. The pellets are stacked, according to each nuclear core's design specifications, into tubes of corrosion-resistant metal alloy. The tubes are sealed to contain the fuel pellets: these tubes are called fuel rods.

The finished fuel rods are grouped in special fuel assemblies that are then used to build up the nuclear fuel core of a power reactor. The metal used for the tubes depends on the design of the reactor - stainless steel was used in the past, but most reactors now use a zirconium. For the most common types of reactors the tubes are assembled into bundles with the tubes spaced precise distances apart. These bundles are then given a unique identification number, which enables them to be tracked from manufacture through use and into disposal.

Pressurized water reactor fuel consists of cylindrical rods put into bundles. A uranium oxide ceramic is formed into pellets and inserted into zirconium alloy tubes that are bundled together. The zirconium alloy tubes are about 1 cm in diameter, and the fuel cladding gap is filled with helium gas to improve the conduction of heat from the fuel to the cladding. There are about 179-264 fuel rods per fuel bundle and about 121 to 193 fuel bundles are loaded into a reactor core. Generally, the fuel bundles consist of fuel rods bundled 14x14 to 17x17. PWR fuel bundles are about 4 meters in length. The zirconium alloy tubes are pressurized with helium to try to minimize pellet cladding interaction which can lead to fuel rod failure over long periods [11].

In boiling water reactors, the fuel is similar to PWR fuel except that the bundles are "canned"; that is, there is a thin tube surrounding each bundle. This is primarily done to prevent local density variations from effecting neutrinos and thermal hydraulics of the nuclear core on a global scale. In modern BWR fuel bundles, there are either 91, 92, or 96 fuel rods per assembly depending on the manufacturer. A range between 368 assemblies for the smallest and 800 assemblies for the largest U.S. BWR forms the reactor core. Each BWR fuel rod is back filled with helium to a pressure of about three atmospheres (300 kPa) [11] .

3.2.4 Moderator

A neutron moderator is a medium which reduces the velocity of fast neutrons, thereby turning them into thermal neutrons capable of sustaining a nuclear chain reaction involving uranium-235. A good neutron moderator is a material full of atoms with light nuclei which do not easily absorb neutrons. The neutrons strike the nuclei and bounce off. After sufficient impacts, the velocity of the neutron will be comparable to the thermal velocities of the nuclei; this neutron is then called a thermal neutron.

The light water reactor uses ordinary water, also called light water, as its neutron moderator. The light water absorbs too many neutrons to be used with unenriched natural uranium, and therefore uranium enrichment or nuclear reprocessing becomes necessary to operate such reactors, increasing overall costs. This differentiates it from a heavy water reactor, which uses heavy water as a neutron moderator. While ordinary water has some heavy water molecules in it, it is not enough to be important in most applications. In pressurized water reactors the coolant water is used as a moderator by letting the neutrons undergo multiple collisions with light hydrogen atoms in the water, losing speed in the process. This moderating of neutrons will happen more often when the water is denser, because more collisions will occur.

The use of water as a moderator is an important safety feature of PWRs, as any increase in temperature causes the water to expand and become less dense; thereby reducing the extent to which neutrons are slowed down and hence reducing the reactivity in the reactor. Therefore, if reactivity increases beyond normal, the reduced moderation of neutrons will cause the chain reaction to slow down, producing less heat. This property, known as the negative temperature coefficient of reactivity, makes PWR reactors very stable. In event of a loss-of-coolant accident, the moderator is also lost and the active fission reaction will stop. Heat is still produced after the chain reaction stops from the radioactive byproducts of fission, at about 5% of rated power. This "decay heat" will continue for 1 to 3 years after shut down, whereupon the reactor finally reaches "full cold shutdown". Decay heat, while dangerous and strong enough to melt the core, is not nearly as intense as an active fission reaction. During the post shutdown period the reactor requires cooling water to be pumped or the reactor will overheat. If the temperature exceeds 2200 degrees Celsius, cooling water will break down to hydrogen and oxygen, which can form a (chemically) explosive mixture. Decay heat is a major risk factor in LWR safety record [11] .

3.3 Pressurized water reactors

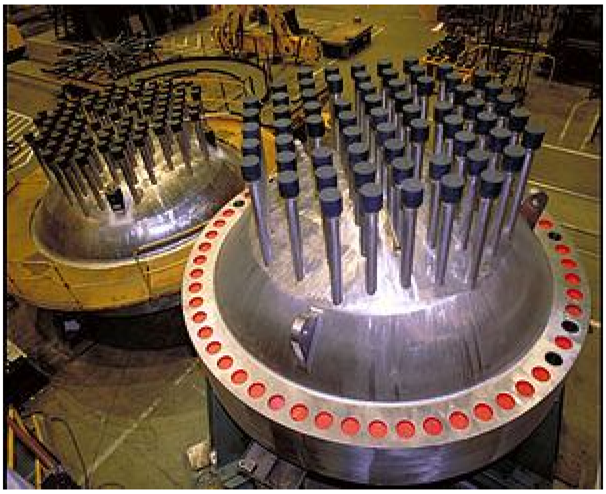


Figure (3.2) : nuclear regulatory commission image of pressurized water reactor vessel heads

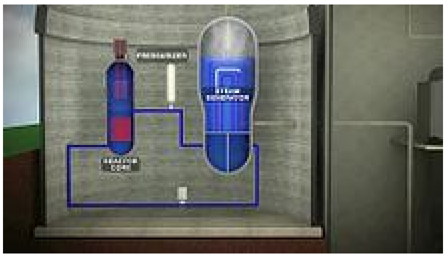


Figure (3.3) : An animation of a PWR power station with cooling towers

constitute the large majority of all Western nuclear power plants and are one of three types of light water reactor (LWR), the other types being boiling water reactors (BWRs) and supercritical water reactors(SCWRs). In a PWR, the primary coolant (water) is pumped under high pressure to the reactor core where it is heated by the energy generated by the fission of atoms. The heated water then flows to a steam generator where it transfers its thermal energy to a secondary system where steam is generated and flows to turbines which, in turn, spin an electric generator. In contrast to a boiling water reactor, pressure in the primary coolant loop prevents the water from boiling within the reactor. All LWRs use ordinary water as both coolant and neutron moderator [12].

PWRs currently operating in the United States are considered Generation II reactors. Russia's VVER reactors are similar to U.S. PWRs. France operates many PWRs to generate the bulk of its electricity.

3.3.1 Design

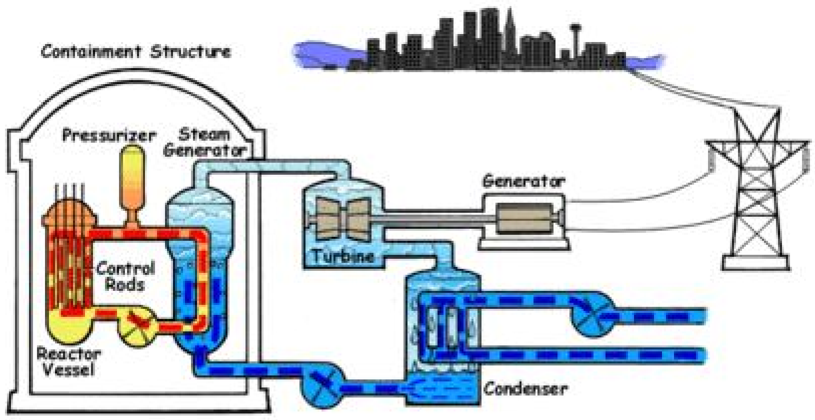


Figure (3.4) : Design for PWR

In fig (3.4) shown Pictorial explanation of power transfer in a pressurized water reactor. Primary coolant is in orange and the secondary coolant (steam and later feed water) is in blue .

In a nuclear power station, the pressurized steam is fed through a steam turbine which drives an electrical generator connected to the electric grid for distribution. After passing through the turbine the secondary coolant (water-steam mixture) is cooled down and condensed in a condenser. The condenser converts the steam to a liquid so that it can be pumped back into the steam generator, and maintains a vacuum at the turbine outlet so that the pressure drop across the turbine, and hence the energy extracted from the steam, is maximized. Before being fed into the steam generator, the condensed steam (referred to as feed water) is sometimes preheated in order to minimize thermal shock.[12]

Two things are characteristic for the pressurized water reactor (PWR) when compared with other reactor types: coolant loop separation from the steam system and pressure inside the primary coolant loop. In a PWR, there are two separate coolant loops (primary and secondary), which are both filled with dematerialized/deionized water. A boiling water reactor, by contrast, has only one coolant loop, while more exotic designs such as breeder reactors use substances other than water for coolant and moderator (e.g. sodium in its liquid state as coolant or graphite as a moderator). The pressure in the primary coolant loop is typically 15–16 megapascals (150–160 bar), which is notably higher than in other nuclear reactors, and nearly twice that of a boiling water reactor (BWR). As an effect of this, only localized boiling occurs and steam will recon dense promptly in the bulk fluid. By contrast, in a boiling water reactor the primary coolant is designed to boil.[13]

3.2.2 PWR reactor design

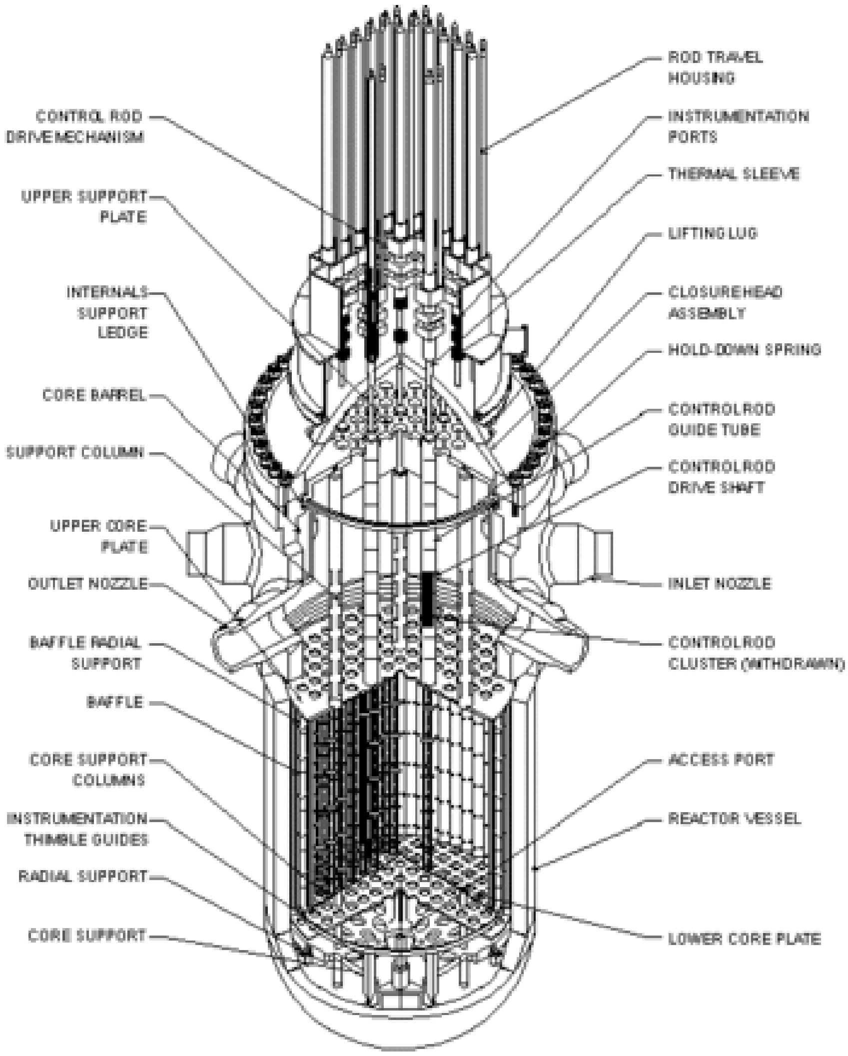


Figure (3.5) : PWR reactor vessel

3.3.3 Coolant

Light water is used as the primary coolant in a PWR. It enters the bottom of the reactor core at about 548 K (275 °C or 530 °F) and is heated as it flows upwards through the reactor core to a temperature of about 588 K (315 °C or 600 °F). The water remains liquid despite the high temperature due to the high pressure in the primary coolant loop, usually around 155 bar (15.5 MPa 153 atm, 2,250 psig). In water, the critical point occurs at around 647 K (374 °C or 705 °F) and 22.064 MPa (3200 PSIA or 218 atm) [14].

3.3.4 Pressurizer

Pressure in the primary circuit is maintained by a pressurizer, a separate vessel that is connected to the primary circuit and partially filled with water which is heated to the saturation temperature (boiling point) for the desired pressure by submerged electrical heaters. To achieve a pressure of 155 bar, the pressurizer temperature is maintained at 345 °C (653 °F), which gives a sub cooling margin (the difference between the pressurizer temperature and the highest temperature in the reactor core) of 30 °C (54 °F). Thermal transients in the reactor coolant system result in large swings in pressurizer liquid volume, total pressurizer volume is designed around absorbing these transients without uncovering the heaters or emptying the pressurizer. Pressure transients in the primary coolant system manifest as temperature transients in the pressurizer and are controlled through the use of automatic heaters and water spray, which raise and lower pressurizer temperature, respectively [15].

3.3.5 Pumps

The coolant is pumped around the primary circuit by powerful pumps, which can consume up to 6 MW each.[12] After picking up heat as it passes through the reactor core, the primary coolant transfers heat in a steam generator to water in a lower pressure secondary circuit, evaporating the secondary coolant to saturated steam — in most designs 6.2 MPa (60 atm, 900 psia), 275 °C (530 °F) — for use in the steam turbine. The cooled primary coolant is then returned to the reactor vessel to be heated again.

3.3.6 Moderator

Pressurized water reactors, like all thermal reactor designs, require the fast fission neutrons to be slowed down (a process called moderation or thermal) in order to interact with the nuclear fuel and sustain the chain reaction. In PWRs the coolant water is used as a moderator by letting the neutrons undergo multiple collisions with light hydrogen atoms in the water, losing speed in the process. This "moderating" of neutrons will happen more often when the water is denser (more collisions will occur). The use of water as a moderator is an important safety feature of PWRs, as an increase in temperature may cause the water to expand, giving greater 'gaps' between the water molecules and reducing the probability of thermalisation—thereby reducing the extent to which neutrons are slowed down and hence reducing the reactivity in the reactor. Therefore, if reactivity increases beyond normal, the reduced moderation of neutrons will cause the chain reaction to slow down, producing less heat. This property, known as the negative temperature coefficient of reactivity, makes PWR reactors very stable. This process is referred to as 'Self-Regulating', i.e. the hotter the coolant becomes, the less reactive the plant becomes, shutting itself down slightly to compensate and vice versa. Thus the plant controls itself around a given temperature set by the position of the control rods.

In contrast, the RBMK reactor design used at Chernobyl, which uses graphite instead of water as the moderator and uses boiling water as the coolant, has a large positive thermal coefficient of reactivity, that increases heat generation when coolant water temperatures increase. This makes the RBMK design less stable than pressurized water reactors. In addition to its property of slowing down neutrons when serving as a moderator, water also has a property of absorbing neutrons, albeit to a lesser degree. When the coolant water temperature increases, the boiling increases, which creates voids. Thus there is less water to absorb thermal neutrons that have already been slowed down by the graphite moderator, causing an increase in reactivity. This property is called the void coefficient of reactivity, and in an RBMK reactor like Chernobyl, the void coefficient is positive, and fairly large, causing rapid transients. This design characteristic of the RBMK reactor is generally seen as one of several causes of the Chernobyl disaster [15].

Heavy water has very low neutron absorption, so heavy water reactors tend to have a positive void coefficient, though the CANDU reactor design mitigates this issue by using unenriched, natural uranium; these reactors are also designed with a number of passive safety systems not found in the original RBMK design.

3.3.7 Fuel

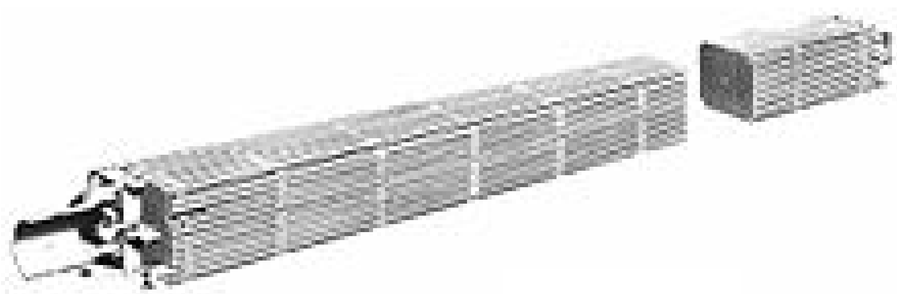


Figure (3.6) : PWR fuel bundle

This fuel bundle is from a pressurized water reactor of the nuclear passenger and cargo ship NS savannah . Designed and built by the Babcock and Wilcox Company .

After enrichment, the uranium dioxide (UO2) powder is fired in a high-temperature, sintering furnace to create hard, ceramic pellets of enriched uranium dioxide. The cylindrical pellets are then clad in a corrosion-resistant zirconium metal alloy Zircaloy which are backfilled with helium to aid heat conduction and detect leakages. Zircaloy is chosen because of its mechanical properties and its low absorption cross section.[9] The finished fuel rods are grouped in fuel assemblies, called fuel bundles, that are then used to build the core of the reactor. A typical PWR has fuel assemblies of 200 to 300 rods each, and a large reactor would have about 150–250 such assemblies with 80–100 tonnes of uranium in all. Generally, the fuel bundles consist of fuel rods bundled 14×14 to 17×17. A PWR produces on the order of 900 to 1,600 MW_e. PWR fuel bundles are about 4 meters in length as shown in fig (3.5) [12] .

Refueling for most commercial PWRs is on an 18–24 month cycle. Approximately one third of the core is replaced each refueling, though some more modern refueling schemes may reduce refuel time to a few days and allow refueling to occur on a shorter periodicity [13] .

3.3.8 Control

In PWRs reactor power can be viewed as following steam (turbine) demand due to the reactivity feedback of the temperature change caused by increased or decreased steam flow. (See: Negative temperature coefficient.) Boron and control rods are used to maintain primary system temperature at the desired point. In order to decrease power, the operator throttles shut turbine inlet valves. This would result in less steam being drawn from the steam generators. This results in the primary loop increasing in temperature. The higher temperature causes less fission and decreases power. This decrease of power will eventually result in primary system temperature returning to its previous steady state value. The operator can control the steady state operating temperature by addition of boric acid and/or movement of control rods.

Reactivity adjustment to maintain 100% power as the fuel is burned up in most commercial PWRs is normally achieved by varying the concentration of boric acid dissolved in the primary reactor coolant. Boron readily absorbs neutrons and increasing or decreasing its concentration in the reactor coolant will therefore affect the neutron activity correspondingly. An entire control system involving high pressure pumps (usually called the charging and letdown system) is required to remove water from the high pressure primary loop and re-inject the water back in with differing concentrations of boric acid. The reactor control rods, inserted through the reactor vessel head directly into the fuel bundles, are moved for the following reasons:

- To start up the reactor.
- To shut down the primary nuclear reactions in the reactor.

- To accommodate short term transients such as changes to load on the turbine.
- The control rods can also be used:
- To compensate for nuclear poison inventory.
- To compensate for nuclear fuel depletion.

However, these effects are more usually accommodated by altering the primary coolant boric acid concentration.

In contrast, BWRs have no boron in the reactor coolant and control the reactor power by adjusting the reactor coolant flow rate.

3.3.9 Advantages

PWR reactors are very stable due to their tendency to produce less power as temperatures increase; this makes the reactor easier to operate from a stability standpoint.

PWR turbine cycle loop is separate from the primary loop, so the water in the secondary loop is not contaminated by radioactive materials.

PWRs can passively scram the reactor in the event that offsite power is lost to immediately stop the primary nuclear reaction. The control rods are held by electromagnets and fall by gravity when current is lost; full insertion safely shuts down the primary nuclear reaction.PWR technology is favoured by nations seeking to develop a nuclear navy, the compact reactors fit well in nuclear submarines and other nuclear ships.

3.3.10 Disadvantages

The coolant water must be highly pressurized to remain liquid at high temperatures. This requires high strength piping and a heavy pressure vessel and hence increases construction costs. The higher pressure can increase the consequences of a loss-of-coolant accident. The reactor pressure vessel is manufactured from ductile steel but, as the plant is operated, neutron flux from the reactor causes this steel to become less ductile. Eventually the ductility of the steel will reach limits determined by the applicable boiler and pressure vessel standards, and the pressure vessel must be repaired or replaced. This might not be practical or economic, and so determines the life of the plant [15].

- The high temperature water coolant with boric acid dissolved in it is corrosive to carbon steel (but not stainless steel); this can cause radioactive corrosion products to circulate in the primary coolant loop. This not only limits the lifetime of the reactor, but the systems that filter out the corrosion products and adjust the boric acid concentration add significantly to the overall cost of the reactor and to radiation exposure. In one instance, this has resulted in severe corrosion to control rod drive mechanisms when the boric acid solution leaked through the seal between the mechanism itself and the primary system. [15][16].

- Natural uranium is only 0.7% uranium-235, the isotope necessary for thermal reactors. This makes it necessary to enrich the uranium fuel, which significantly increases the costs of fuel production. The requirement to enrich fuel for PWRs also presents a serious proliferation risk.
- Because water acts as a neutron moderator, it is not possible to build a fast neutron reactor with a PWR design. A reduced moderation water reactor may however achieve a breeding greater than unity, though this reactor design has disadvantages of its own. [17]

3.4 Boiling water reactor

The boiling water reactor (BWR) is a type of light water nuclear reactor used for the generation of electrical power. It is the second most common type of electricity-generating nuclear reactor after the pressurized water reactor (PWR), also a type of light water nuclear reactor. The main difference between a BWR and PWR is that in a BWR, the reactor core heats water, which turns to steam and then drives a steam turbine. In a PWR, the reactor core heats water, which does not boil. This hot water then exchanges heat with a lower pressure water system, which turns to steam and drives the turbine as shown in fig (37).

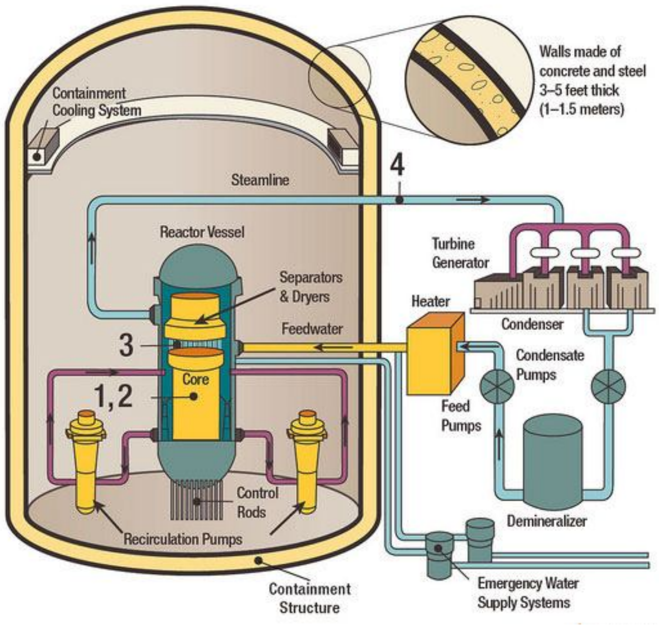


Figure (3.7) : Schematic diagram of a boiling water (BWE)

3.4.1 Overview

The *boiling water reactor* (BWR) uses demineralized water as a coolant and neutron moderator. Heat is produced by nuclear fission in the reactor core, and this causes the cooling water to boil, producing steam. The steam is directly used to drive a turbine, after which it is cooled in a condenser and converted back to liquid water. This water is then returned to the reactor core, completing the loop. The cooling water is maintained at about 75 atm (7.6 MPa, 1000–1100 psi) so that it boils in the core at about 285 °C (550 °F). In comparison, there is no significant boiling allowed in a PWR (Pressurized Water Reactor) because of the high pressure maintained in its primary loop—approximately 158 atm (16 MPa, 2300 psi). The core damage frequency of the reactor was estimated to be between 10^{-4} and 10^{-7} (i.e., one core damage accident per every 10,000 to 10,000,000 reactor years) [18].

3.4.2 Components

Steam exiting the turbine flows into condensers located underneath the low pressure turbines where the steam is cooled and returned to the liquid state (condensate). The condensate is then pumped through feed water heaters that raise its temperature using extraction steam from various turbine stages. Feed water from the feed water heaters enters the reactor pressure vessel (RPV) through nozzles high on the vessel, well above the top of the nuclear fuel assemblies (these nuclear fuel assemblies constitute the "core") but below the water level.

The feed water enters into the down comer or annulus region and combines with water exiting the moisture separators. The feed water sub cools the saturated water from the moisture separators. This water now flows down the down comer or annulus region, which is separated from the core by a tall shroud. The water then goes through either jet pumps or internal recirculation pumps that provide additional pumping power (hydraulic head). The water now makes a 180 degree turn and moves up through the lower core plate into the nuclear core where the fuel elements heat the water. Water exiting the fuel channels at the top guide is saturated with a steam quality of about 15%. Typical core flow may be 45,000,000 kg/h (100,000,000 lb/h) with 6,500,000 kg/h (14,500,000 lb/h) steam flow. However, core-average void fraction is a significantly higher fraction (~40%). These sort of values may be found in each plant's publicly available Technical Specifications, Final Safety Analysis Report, or Core Operating Limits Report.

The heating from the core creates a thermal head that assists the recirculation pumps in recirculating the water inside of the RPV. A BWR can be designed with no recirculation pumps and rely entirely on the thermal head to recirculate the water inside of the RPV. The forced recirculation head from the recirculation pumps is very useful in controlling power, however, and allows achieving higher power levels that would not otherwise be possible. The thermal power level is easily varied by simply increasing or decreasing the forced recirculation flow through the recirculation pumps.

The two phase fluid (water and steam) above the core enters the riser area, which is the upper region contained inside of the shroud. The height of this region may be increased to increase the thermal natural recirculation pumping head. At the top of the riser area is the moisture separator. By swirling the two phase flow in cyclone separators, the steam is separated and rises upwards towards the steam dryer while the water remains behind and flows horizontally out into the down comer or annulus region. In the down comer or annulus region, it combines with the feed water flow and the cycle repeats.

The saturated steam that rises above the separator is dried by a chevron dryer structure. The "wet" steam goes through a tortuous path where the water droplets are slowed down and directed out into the down comer or annulus region. The "dry" steam then exits the RPV through four main steam lines and goes to the turbine.

3.4.2.1 Control systems

Reactor power is controlled via two methods: by inserting or withdrawing control rods and by changing the water flow through the reactor core.

Positioning (withdrawing or inserting) control rods is the normal method for controlling power when starting up a BWR. As control rods are withdrawn, neutron absorption decreases in the control material and increases in the fuel, so reactor power increases. As control rods are inserted, neutron absorption increases in the control material and decreases in the fuel, so reactor power decreases. Some early BWRs and the proposed ESBWR (Economic Simplified BWR made by General Electric Hitachi) designs use only natural circulation with control rod positioning to control power from zero to 100% because they do not have reactor recirculation systems. Fine reactivity adjustment would be accomplished by modulating the recirculation flow of the reactor vessel [19] .

Changing (increasing or decreasing) the flow of water through the core is the normal and convenient method for controlling power from approximately 30% to 100% reactor power. When operating on the so-called "100% rod line," power may be varied from approximately 30% to 100% of rated power by changing the reactor recirculation system flow by varying the speed of the recirculation pumps or modulating flow control valves. As flow of water through the core is increased, steam bubbles ("voids") are more quickly removed from the core, the amount of liquid water in the core increases, neutron moderation increases, more neutrons are slowed down to be absorbed by the fuel, and reactor power increases. As flow of water through the core is decreased, steam voids remain longer in the core, the amount of liquid water in the core decreases, neutron moderation decreases, fewer neutrons are slowed down to be absorbed by the fuel, and reactor power decreases [19].

Reactor pressure in a BWR is controlled by the main turbine or main steam bypass valves. Unlike a PWR, where the turbine steam demand is set manually by the operators, in a BWR, the turbine valves will modulate to maintain reactor pressure at a set point. Under this control mode, the turbine will automatically follow reactor power changes. When the turbine is offline or trips, the main steam bypass/dump valves will open to direct steam directly to the condenser. These bypass valves will automatically or manually modulate as necessary to maintain reactor pressure and control the reactor's heat up and cool down rates while steaming is still in progress.

Reactor water level is controlled by the main feed water system. From about 0.5% power to 100% power, feed water will automatically control the water level in the reactor. At low power conditions, the feed water controller acts as a simple PID control by watching reactor water level. At high power conditions, the controller is switched to a "Three-Element" control mode, where the controller looks at the current water level in the reactor, as well as the amount of water going in and the amount of steam leaving the reactor. By using the water injection and steam flow rates, the feed water control system can rapidly anticipate water level deviations and respond to maintain water level within a few inches of set point. If one of the two feed water pumps fails during operation, the feed water system will command the recirculation system to rapidly reduce core flow, effectively reducing reactor power from 100% to 50% in a few seconds. At this power level a single feed water pump can maintain the core water level. If all feed water is lost, the reactor will scram and the Emergency Core Cooling System is used to restore reactor water level.

3.4.2.2 Steam turbines

Steam produced in the reactor core passes through steam separators an d dryer plates above the core and then directly to the turbine, which is part of the reactor circuit. Because the water around the core of a reactor is always contaminated with traces of radio nuclides, the turbine must be shielded during normal operation, and radiological protection must be provided during maintenance. The increased cost related to operation and maintenance of a BWR tends to balance the savings due to the simpler design and greater thermal efficiency of a BWR when compared with a PWR. Most of the radioactivity in the water is very short-lived (mostly N-16, with a 7-second half-life), so the turbine hall can be entered soon after the reactor is shut down.

3.4.2.3 Reactor core

A modern BWR fuel assembly comprises 74 to 100 fuel rods, and there are up to approximately 800 assemblies in a reactor core, holding up to approximately 140 short tons of low. The number of fuel assemblies in a specific reactor is based on considerations of desired reactor power output, reactor core size and reactor power density.

3.4.2.4 Safety systems

A modern reactor has many safety systems that are designed with a defence in depth philosophy, which is a design philosophy that is integrated throughout construction and commissioning.

A BWR is similar to a pressurized water reactor (PWR) in that the reactor will continue to produce heat even after the fission reactions have stopped, which could make a core damage incident possible. This heat is produced by the radioactive decay of fission products and materials that have been activated by neutron absorption. BWRs contain multiple safety systems for cooling the core after emergency shut down.

3.4.2.5 Refueling systems

The reactor fuel rods are occasionally replaced by removing them from the top of the containment vessel. A typical fuel cycle lasts 18–24 months, with about one third of fuel assemblies being replaced during a refueling outage. The remaining fuel assemblies are shuffled to new core locations to maximize the efficiency and power produced in the next fuel cycle.

Because they are hot both radioactively and thermally, this is done via cranes and under water. For this reason the spent fuel storage pools are above the reactor in typical installations. They are shielded by water several times their height, and stored in rigid arrays in which their geometry is controlled to avoid criticality. In the Fukushima reactor incident this became problematic because water was lost from one or more spent fuel pools and the earthquake could have altered the geometry. The fact that the fuel rods' cladding is a zirconium alloy was also problematic since this element can react with steam at extreme temperatures to produce hydrogen, which can ignite with oxygen in the air. Normally the fuel rods are kept sufficiently cool in the reactor and spent fuel pools that this is not a concern, and the cladding remains intact for the life of the rod [20].

3.4.3 Simplified boiling water reactor

Parallel to the development of the ABWR, General Electric also developed a different concept, known as the *simplified boiling water reactor*(SBWR). This smaller 600 megawatt electrical reactor was notable for its incorporation—for the first time ever in a light water reactor—of "passive safety" design principles. The concept of passive safety means that the reactor, rather than requiring the intervention of active systems, such as emergency injection pumps, to keep the reactor within safety margins, was instead designed to return to a safe state solely through operation of natural forces if a safety-related contingency developed.

For example, if the reactor got too hot, it would trigger a system that would release soluble neutron absorbers (generally a solution of borated materials, or a solution of borax), or materials that greatly hamper a chain reaction by absorbing neutrons, into the reactor core. The tank containing the soluble neutron absorbers would be located above the reactor, and the absorption solution, once the system was triggered, would flow into the core through force of gravity, and bring the reaction to a near-complete stop. Another example was the Isolation Condenser system, which relied on the principle of hot water/steam rising to bring hot coolant into large heat exchangers located above the reactor in very deep tanks of water, thus accomplishing residual heat removal. Yet another example was the omission of recirculation pumps within the core; these pumps were used in other BWR designs to keep cooling water moving; they were expensive, hard to reach to repair, and could occasionally fail; so as to improve reliability, the ABWR incorporated no less than 10 of these recirculation pumps, so that even if several failed, a sufficient number would remain serviceable so that an unscheduled shutdown would not be necessary, and the pumps could be repaired during the next refueling outage. Instead, the designers of the *simplified boiling water reactor* used thermal analysis to design the reactor core such that natural circulation (cold water falls, hot water rises) would bring water to the center of the core to be boiled.

The ultimate result of the passive safety features of the SBWR would be a reactor that would not require human intervention in the event of a major safety contingency for at least 48 hours following the safety contingency; thence, it would only require periodic refilling of cooling water tanks located completely outside of the reactor, isolated from the cooling system, and designed to remove reactor waste heat through evaporation [20].

3.4.4 Advantages and disadvantages

* Advantages

- The reactor vessel and associated components operate at a substantially lower pressure (about 75 times atmospheric pressure) compared to a PWR (about 158 times atmospheric pressure).
- Pressure vessel is subject to significantly less irradiation compared to a PWR, and so does not become as brittle with age.
- Operates at a lower nuclear fuel temperature.

- Fewer components due to no steam generators and no pressurizer vessel. (Older BWRs have external recirculation loops, but even this piping is eliminated in modern BWRs, such as the ABWR.)
- Lower risk (probability) of a rupture causing loss of coolant compared to a PWR, nd lower risk of core damage should such a rupture occur. This is due to fewer pipes, fewer large diameter pipes, fewer welds and no steam generator tubes.
- NRC assessments of limiting fault potentials indicate if such a fault occurred, the average BWR would be less likely to sustain core damage than the average PWR due to the robustness and redundancy of the Emergency Core Cooling System (ECCS).
- Measuring the water level in the pressure vessel is the same for both normal and emergency operations, which results in easy and intuitive assessment of emergency conditions.
- Can operate at lower core power density levels using natural circulation without forced flow.
- A BWR may be designed to operate using only natural circulation so that recirculation pumps are eliminated entirely. (The new ESBWR design uses natural circulation.)
- BWRs do not use boric acid to control fission burn-up, leading to less possibility of corrosion within the reactor vessel and piping. (Corrosion from boric acid must be carefully monitored in PWRs; it has been demonstrated that reactor vessel head corrosion can occur if the reactor vessel head is not properly maintained. See Davis-Besse. Since BWRs do not utilize boric acid, these contingencies are eliminated.)
- BWRs generally have *N*-2 redundancy on their major safety-related systems, which normally consist of four "trains" of components. This generally means that up to two of the four components of a safety system can fail and the system will still perform if called upon [21].

* Disadvantages

- BWRs require more complex calculations for managing consumption of nuclear fuel during operation due to "two phase (water and steam) fluid flow" in the upper part of the core. This also requires more instrumentation in the reactor core.
- Larger pressure vessel than for a PWR of similar power, with correspondingly higher cost, in particular for older models that still use a main steam generator and associated piping.
- Contamination of the turbine by short-lived activation products. This means that shielding and access control around the steam turbine are required during normal operations due to the radiation levels arising from the steam entering directly from the reactor core. This is a moderately minor concern, as most of the radiation flux is due to Nitrogen-16, which

has a half-life measured in seconds, allowing the turbine chamber to be entered into within minutes of shutdown.

- Though the present fleet of BWRs is said to be less likely to suffer core damage from the "1 in 100,000 reactor-year" limiting fault than the present fleet of PWRs, (due to increased ECCS robustness and redundancy) there have been concerns raised about the pressure containment ability of the as-built, unmodified Mark I containment – that such may be insufficient to contain pressures generated by a limiting fault combined with complete ECCS failure that results in extremely severe core damage. In this double failure scenario, assumed to be extremely unlikely prior to the Fukushima I nuclear accidents, an unmodified Mark I containment can allow some degree of radioactive release to occur. This is supposed to be mitigated by the modification of the Mark I containment; namely, the addition of an outgas stack system that, if containment pressure exceeds critical setpoints, is supposed to allow the orderly discharge of pressurizing gases after the gases pass through activated carbon filters designed to trap radionuclides.
- Control rods are inserted from below for current BWR designs. There are two available hydraulic power sources that can drive the control rods into the core for a BWR under emergency conditions. There is a dedicated high pressure hydraulic accumulator and also the pressure inside of the reactor pressure vessel available to each control rod. Either the dedicated accumulator (one per rod) or reactor pressure is capable of fully inserting each rod. Most other reactor types use top entry control rods that are held up in the withdrawn position by electromagnets, causing them to fall into the reactor by gravity if power is lost [21].

CHAPTER FOUR

HEAVY WATER REATOR

4.1 heavy water reactor

A pressurized heavy-water reactor (PHWR) is a nuclear power reactor, commonly using unenriched natural uranium as its fuel, that uses heavy water (deuterium oxide D_2O) as its coolant and moderator. The heavy-water coolant is kept under pressure, allowing it to be heated to higher temperatures without boiling, much as in a Pressurized water reactor. While heavy water is significantly more expensive than ordinary light water, it yields greatly enhanced neutron economy, allowing the reactor to operate without fuel-enrichment facilities (mitigating the additional capital cost of the heavy water) and generally enhancing the ability of the reactor to efficiently make use of alternate fuel cycles.

4.2 purpose of using heavy water

The key to maintaining a nuclear reaction within a nuclear reactor is to use the neutrons released during fission to stimulate fission in other nuclei. With careful control over the geometry and reaction rates, this can lead to a self-sustaining chain reaction, a state known as "criticality".

Natural uranium consists of a mixture of various isotopes, primarily ^{238}U and a much smaller amount (about 0.72% by weight) of ^{235}U. ^{238}U can only be fissioned by neutrons that are relatively energetic, about 1 MeV or above. No amount of ^{238}U can be made "critical", however, since it will tend to parasitically absorb more neutrons than it releases by the fission process. ^{235}U, on the other hand, can support a self-sustained chain reaction, but due to the low natural abundance of ^{235}U, natural uranium cannot achieve criticality by itself.

The "trick" to making a working reactor is to slow some of the neutrons to the point where their probability of causing nuclear fission in ^{235}U increases to a level that permits a sustained chain reaction in the uranium as a whole. This requires the use of a neutron moderator, which absorbs some of the neutrons' kinetic energy, slowing them down to an energy comparable to the thermal energy of the moderator nuclei themselves (leading to the terminology of "thermal neutrons" and "thermal reactors"). During this slowing-down process it is beneficial to physically separate the neutrons from the uranium, since ^{238}U nuclei have an enormous parasitic affinity for neutrons in this intermediate energy range (a reaction known as "resonance" absorption). This is a fundamental reason for designing reactors with discrete solid fuel separated by moderator, rather than employing a more homogeneous mixture of the two materials [22].

Water makes an excellent moderator; the hydrogen atoms in the water molecules are very close in mass to a single neutron, and the collisions thus have a very efficient momentum transfer, similar conceptually to the collision of two billiard balls. However, in addition to being a good moderator, water is relatively effective at absorbing neutrons. Using water as a moderator will absorb enough neutrons that there will be too few left over to react with the small amount of ^{235}U in the fuel, again precluding criticality in natural uranium. Instead, in order to fuel a light-water reactor, first the amount of ^{235}U in the uranium must be increased, producing enriched uranium, which generally contains between 3% and 5% ^{235}U by weight (the waste from this process is known as depleted uranium, consisting primarily of ^{238}U). In this enriched form there *is* enough ^{235}U to react with the water-moderated neutrons to maintain criticality.

One complication of this approach is the requirement to build a uranium enrichment facility, which are generally expensive to build and operate. They also present a nuclear proliferation concern; the same systems used to enrich the ^{235}U can also be used to produce much more "pure" weapons-grade material (90% or more ^{235}U), suitable for producing a nuclear bomb. This is not a trivial exercise by any means, but feasible enough that enrichment facilities present a significant nuclear proliferation risk.

An alternative solution to the problem is to use a moderator that does *not* absorb neutrons as readily as water. In this case potentially all of the neutrons being released can be moderated and used in reactions with the ^{235}U, in which case there *is* enough ^{235}U in natural uranium to sustain criticality. One such moderator is heavy water, or deuterium-oxide. Although it reacts dynamically with the neutrons in a similar fashion to light water (albeit with less energy transfer on average, given that heavy hydrogen, or deuterium, is about twice the mass of hydrogen), it already has the extra neutron that light water would normally tend to absorb [22].

4.3 Advantages and disadvantages

The use of heavy-water moderator is the key to the PHWR (pressurized heavy water reactor) system, enabling the use of natural uranium as fuel (in the form of ceramic UO_2), which means that it can be operated without expensive uranium enrichment facilities. Additionally, the mechanical arrangement of the PHWR, which places most of the moderator at lower temperatures, is particularly efficient because the resulting thermal neutrons are "more thermal" than in traditional designs, where the moderator normally runs hot. This means that a PHWR is not only able to "burn" natural uranium and other fuels, but tends to do so more efficiently as well.

Pressurized heavy-water reactors do have some drawbacks. Heavy water generally costs hundreds of dollars per kilogram, though this is a trade-off against reduced fuel costs. The reduced energy content of natural uranium as compared to enriched uranium necessitates more frequent replacement of fuel; this is normally accomplished by use of an on-power refueling system. The increased rate of fuel movement through the reactor also results in higher volumes of spent fuel than in reactors employing enriched uranium; however, as the unenriched fuel was less reactive, the heat generated is less, allowing the spent fuel to be stored much more compactly.[22]

4.4 The Result

After comparison between thermal nuclear reactors whereby theoretical and practical concepts in addition to the operation methods , classification, Mechanism, control ,coolant and safety. we observed the pressure water reactor was the better than the other methods .

4.5 Conclusion and Recommendation

we need this type for research , training, materials testing and the production of radioisotopes for medicine and industry we can use it also in production of materials for nuclear weapons such as weapons-grade plutonium , hydrogen production for use in a hydrogen economy and desalination .

Finally I Recommend to Establish it on the Red Sea coast For The lack of population density in other hand the state needs to the fresh water due to it is far away from the River Nile.

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