“Nuclear Power Generation”

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Abstract

Nuclear power is energy which is produced with the use of a controlled nuclear reaction. Many nations use nuclear power plants to generate electricity for both civilian and military use, and some nations also utilize nuclear power to run parts of their naval fleets, especially submarines. Some people favor an expansion of nuclear power plants because this form of energy is considered cleaner than fossil fuels such as coal, although nuclear power comes with a number of problems which must be addressed, including the safe disposal of radioactive waste products. The process of generation nuclear power starts with the mining and processing of uranium and other radioactive elements. These elements are used to feed the reactor of a nuclear power plant, generating a reaction known as fission which creates intense heat, turning water in the plant into steam. The steam powers steam turbines, which generate electricity and feed the electricity into the electrical grid. When nuclear power is used to power something like a submarine, the reactor runs the engines, with the steam directly powering the engines. In both cases, the reactor requires careful supervision, because runaway nuclear reactions must be stopped as quickly as possible to prevent serious problems. Many nuclear power plants have extensive automated systems which help to identify potential trouble spots, and these systems can also re-route power, turn off parts of the plant, and perform other tasks which make the plant safer and cleaner.

Acknowledgement

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Introduction

Nuclear power is the use of sustained nuclear fission to generate heat and electricity. Nuclear power plants provide about 6% of the world's energy and 13–14% of the world's electricity with the U.S., France, and Japan together accounting for about 50% of nuclear generated electricity. In 2007, the IAEA reported there were 439 nuclear power reactors in operation in the world operating in 31 countries. Also, more than 150 naval vessels using nuclear propulsion have been built.

There is an ongoing debate about the use of nuclear energy. Proponents, such as the World Nuclear Association and IAEA, contend that nuclear power is a sustainable energy source that reduces carbon emissions. Opponents, such as Greenpeace International and NIRS, believe that nuclear power poses many threats to people and the environment.

Nuclear power plant accidents include the Chernobyl disaster (1986), Fukushima Daiichi nuclear disaster (2011), and the Three Mile Island accident (1979). There have also been some nuclear powered submarine mishaps. However, the safety record of nuclear power is good when compared with many other energy technologies. Research into safety improvements is continuing and nuclear fusion may be used in the future.

China has 25 nuclear power reactors under construction, with plans to build many more, while in the US the licenses of almost half its reactors have been extended to 60 years, and plans to build another dozen are under serious consideration. However, Japan's 2011 Fukushima Daiichi nuclear disaster prompted a rethink of nuclear energy policy in many countries. Germany decided to close all its reactors by 2022, and Italy has banned nuclear power. Following Fukushima, the International Energy Agency halved its estimate of additional nuclear generating capacity to be built by 2035.

Power derived from fission or fusion nuclear reactions. More conventionally, nuclear power is interpreted as the utilization of the fission reactions in a nuclear power reactor to produce steam for electric power production, for ship propulsion, or for process heat. Fission reactions involve the breakup of the nucleus of high-mass atoms and yield an energy release which is more than a million fold greater than that obtained from chemical reactions involving the burning of a fuel. Successful control of the nuclear fission reactions utilizes this intensive source of energy.

Fission reactions provide intensive sources of energy. For example, the fissioning of an atom of uranium yields about 200 MeV, whereas the oxidation of an atom of carbon releases only 4 eV. On a weight basis, this 50×10^6 energy ratio becomes about 2.5×10^6. Uranium consists of several isotopes, only 0.7% of which is uranium-235, the fissile fuel currently used in reactors. Even with these considerations, including the need to enrich the fuel to several percent uranium-235, the fission reactions are attractive energy sources when coupled with abundant and relatively cheap uranium ore.

Although the main process of nuclear power is the release of energy in the fission process which occurs in the reactor, there are a number of other important processes, such as mining and waste disposal, which both precede and follow fission. Together they constitute the nuclear fuel cycle.

Power reactors include light water-moderated and cooled reactors (LWRs), including the pressurized water reactor (PWR) and the boiling water reactor (BWR). The high-temperature gas cooled reactor (HTGR) and the liquid metal-cooled fast breeder reactor (LMFBR) have reached a high level of development but are not used for commercial purposes.

Critics of nuclear power consider the radioactive wastes generated by the nuclear industry to be too great a burden for society to bear. They argue that since the high-level wastes will contain highly toxic materials with long half-lives, such as a few tenths of one percent of plutonium that was in the irradiated fuel, the safekeeping of these materials must be assured for time periods longer than social orders have existed in the past. Nuclear proponent's answer that the time required for isolation is much shorter, since only 500 to 1000 years is needed before the hazard posed by nuclear waste falls below that posed by common natural ore deposits in the environment.

Nuclear power facilities present a potential hazard rarely encounted with other facilities; that is, radiation. A major health hazard would result if, for instance, a significant fraction of the core inventory of a power reactor were released to the atmosphere. Such a release of radioactivity is clearly unacceptable, and steps are taken to assure it could never happen. These include use of engineered safety systems, various construction and design codes, regulations on reactor operation, and periodic maintenance and inspection.

Fission Reactions

When large atomic nuclei are hit with neutrons they can become highly unstable if the neutron is absorbed by the nucleus. The larger unstable nucleus breaks into two smaller 'daughter' nuclei and also release more neutrons, as well as beta and alpha particles and gamma. The two smaller atoms formed are themselves usually unstable and radioactive. The nuclear fission equations below are a gross simplification of the process. This process is called nuclear fission and because it is accompanied by an enormous release of energy, it forms the basis of nuclear power. The radioisotopeUuranium-235 is particularly useful for energy generation by nuclear fission. Much of the energy released is initially the kinetic energy of the fission fragments, but collisions, radioactive decay etc. result in most of it changing to heat and some as electromagnetic radiation.

The process of fission occurs when a nucleus splits into smaller pieces. Fission can be induced by a nucleus capturing slow moving neutrons, which results in the nucleus becoming very unstable.

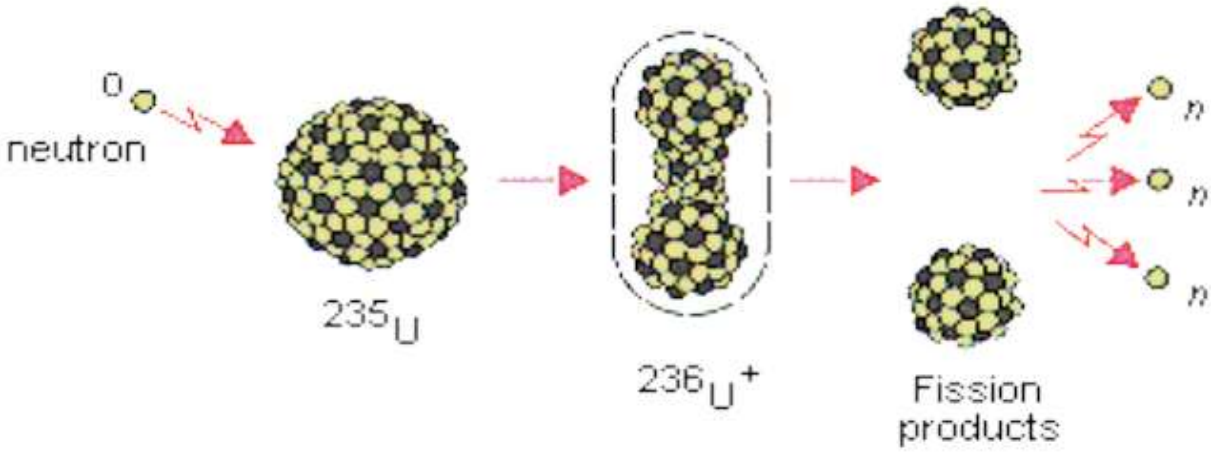


Figure-1: Fission Reactions Process

The following equations represent fission reactions, where n is neutron. All these fission reactions also release a large amount of energy.

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + Energy$$

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{131}_{50}Sn + {}^{103}_{42}Mo + 2\,{}^{1}_{0}n + Energy$$

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{137}_{52}Te + {}^{97}_{40}Zr + 2\,{}^{1}_{0}n + Energy$$

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{138}_{54}Xe + {}^{95}_{38}Sr + 3\,{}^{1}_{0}n + Energy$$

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{152}_{60}Nd + {}^{81}_{32}Ge + 3\,{}^{1}_{0}n + Energy$$

There are two types of fission reaction exist as

(i) **Spontaneous Fission**: Some radioisotopes contain nuclei which are highly unstable and decay spontaneously by splitting into 2 smaller nuclei. Such spontaneous decays are accompanied by the release of neutrons.

(ii) **Induced Fission**: Nuclear fission can be induced by bombarding atoms with neutrons. The nuclei of the atoms then split into 2 equal parts. Induced fission decays are also accompanied by the release of neutrons.

The fission of a heavy nucleus requires a total input energy of about 7 to 8 MeV to initially overcome the strong force which holds the nucleus into a spherical or nearly spherical shape. Deform it into a two-lobed ("peanut") shape. The lobes separate from each other, pushed by their mutual positive charge to a critical distance, beyond which the short range strong force can no longer hold them together. The process of their separation proceeds by the energy of the (longer range) electromagnetic repulsion between the fragments. The result is two fission fragments moving away from each other (+ a few neutrons)

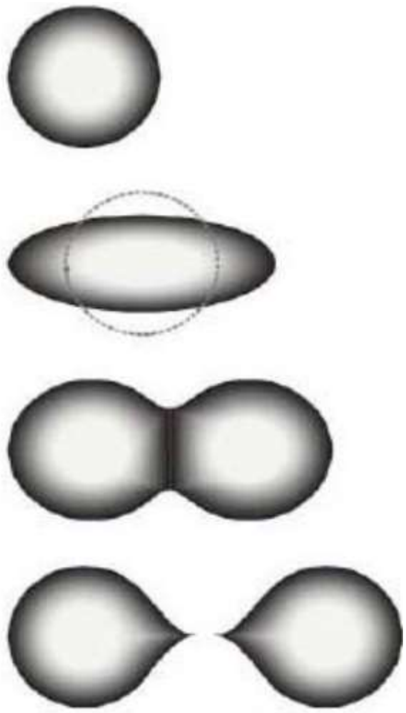


Figure-2: The Splitting of the Atomic Nucleus

The splitting of the atomic nucleus (nuclear fission) produces a lot of energy. This can then be used to make electricity from the heat extracted from a nuclear reactor (by using it to boil water, producing steam, the pressure from which can be used to turn turbines (so that electricity can be produced by electromagnetic induction)).

This is called nuclear power or atomic power.

Spontaneous fission is fission that occurs naturally. As the name suggests, spontaneous fission follows exactly the same process as induced nuclear fission, except that it occurs without the atom having been struck by a neutron or other particle. Spontaneous fissions release neutrons as all fissions do, and so if a critical mass is present, a spontaneous fission can initiate a chain reaction.

Important Characteristics of Fission Reactions

(1) Mass Distribution of Fragments

Fission fragments have a double bell distribution as a function of A (Mass Number). Note that they are unstable, as are neutron rich they decay towards stable nuclei by a chain of beta decays. This yields the so called "fission products". Some fifty per cent of fission products have decay times less than one year, the rest has lifetimes that can be as long as million years,

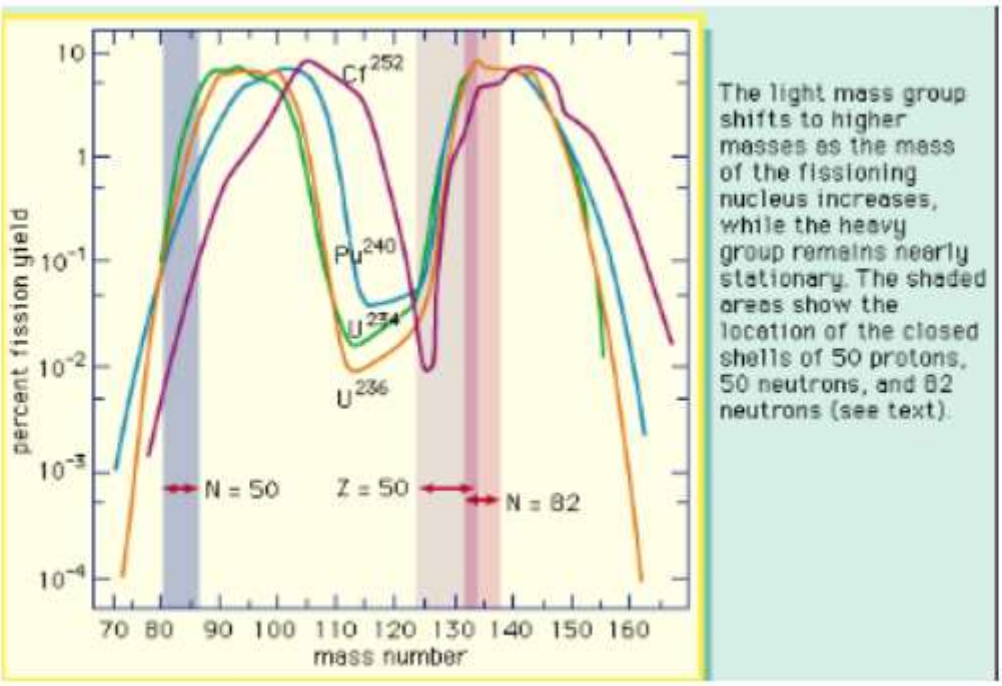
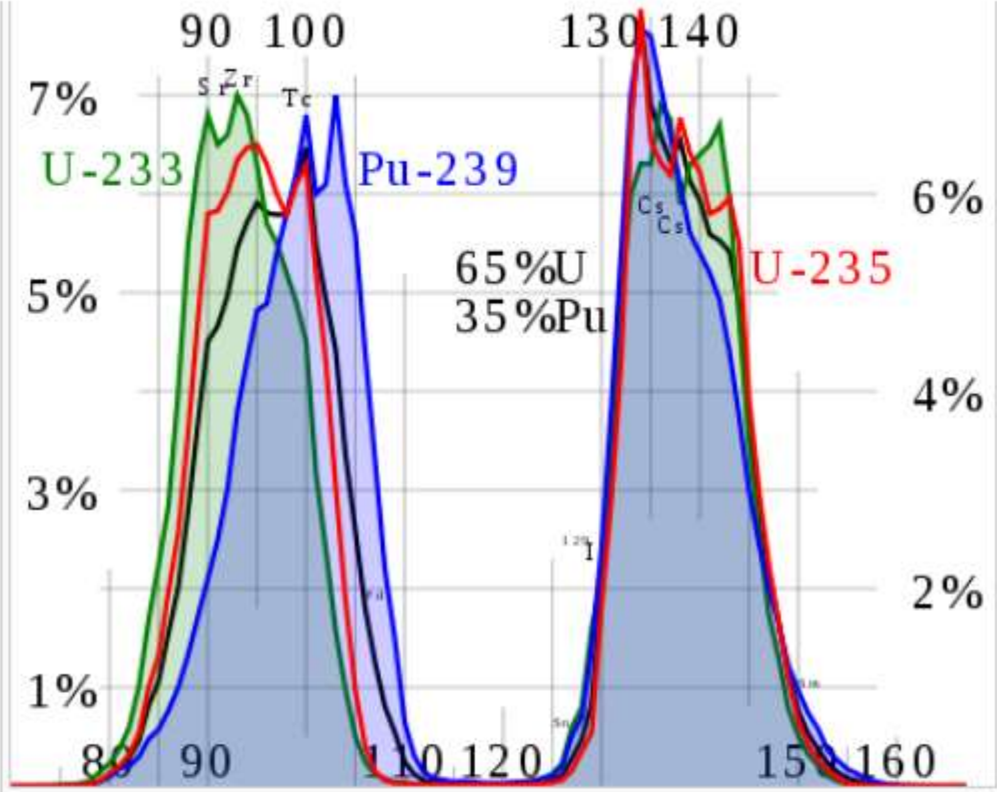


Figure-3: Mass Distribution of Fission Fragments



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-233 used in the thorium cycle

Figure-4: Fission product yields by mass for thermal neutron fission of ^{235}U, ^{239}Pu, a combination of the two typical of current nuclear power reactors, and ^{233}U used in the thorium cycle.

(2) Number of Emitted Neutrons

One distinguishes two types of neutrons from fission such as

(i) Prompt Neutrons,

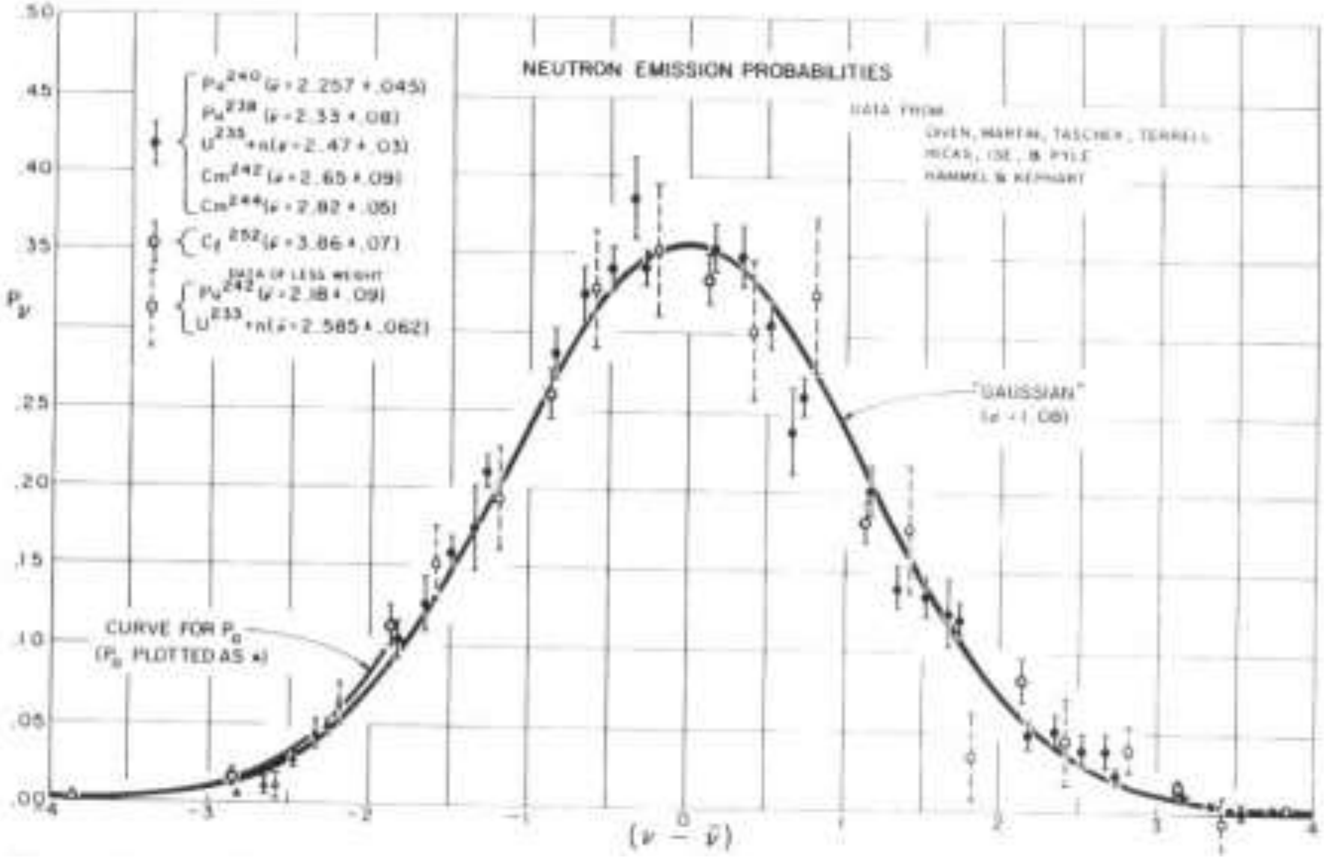
They are those accompanying the two nuclear fragments as the 2n in

$^{235}U+n\rightarrow\, ^{93}Rb + \,^{141}Cs+2n$

In the case of ^{235}U, there are on the average 2.42 prompt neutrons

(ii) Delayed Neutrons

These are associated with the beta decay of the fission products. Indeed, after prompt fission neutron emission the residual fragments are still neutron rich. They undergo a ß decay chain. In some cases the available energy in the ß decay is high enough for leaving the residual nucleus in such a highly excited state that neutron emission instead of gamma emission occurs. (Beta delayed neutron emission) Delayed neutrons have delays of order seconds. They are about 1/100 fissions. Delayed neutrons are essential for the control of nuclear reactors.



Figue-5: Distribution of fission neutrons. Even though the average number of neutrons ν changes with the fissioning nucleus; the distribution about the average is independent of the original nucleus.

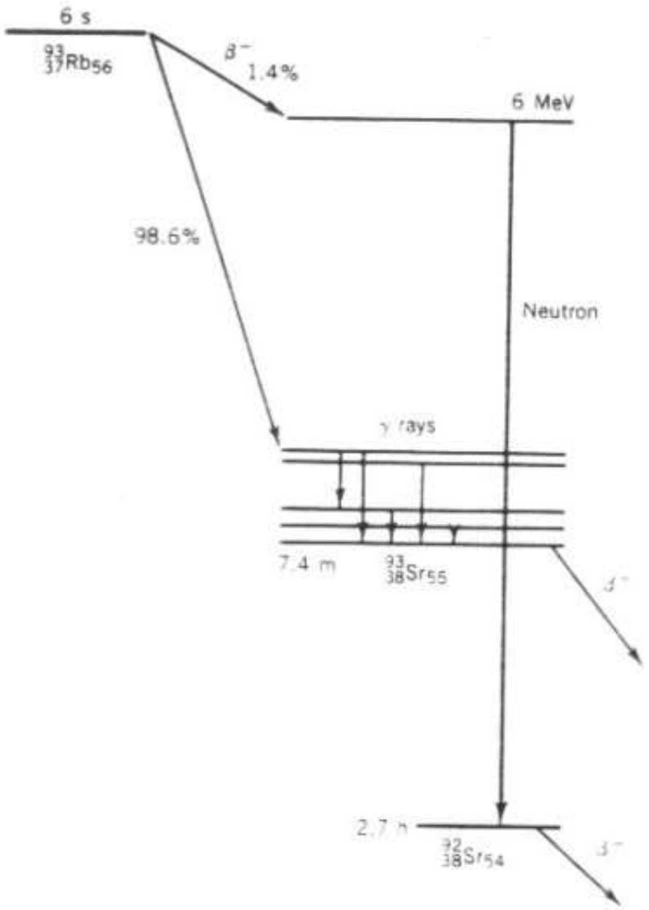


Figure-6: Delayed Neutron Emission from ^{93}Rb. After the original β decay, the excited state of ^{93}Sr has enough energy to decay by neutron emission to ^{92}Sr. The neutrons are delayed relative to the prompt fission neutrons by a time characteristic of the mean lifetime of ^{93}Rb

(3) Radioactive Decay Processes

The initial fission products are highly radioactive and decay toward stable isobars by emitting many β and γ radiations (which contribute ultimately to the total energy release in fission). Some sample decay chains are

$$^{93}\mathrm{Rb} \xrightarrow{6\ \mathrm{s}} {}^{93}\mathrm{Sr} \xrightarrow{7\ \mathrm{min}} {}^{93}\mathrm{Y} \xrightarrow{10\ \mathrm{h}} {}^{93}\mathrm{Zr} \xrightarrow{10^6\ \mathrm{y}} {}^{93}\mathrm{Nb}$$

$$^{141}\mathrm{Cs} \xrightarrow{25\ \mathrm{s}} {}^{141}\mathrm{Ba} \xrightarrow{18\ \mathrm{min}} {}^{141}\mathrm{La} \xrightarrow{4\ \mathrm{h}} {}^{141}\mathrm{Ce} \xrightarrow{33\ \mathrm{d}} {}^{141}\mathrm{Pr}$$

These radioactive products are the waste products of nuclear reactors. Many decay very quickly, but others have long half-lives, especially near the stable member of series.

(4) Fission Cross-section

^{235}U will fission (n, f) at all energies of the absorbed neutron. It is a Fissile Material. Note the 1/v behavior of fission cross section at low velocities, typical of exothermal processes. ^{235}U fission cross section can grow Very large, to 500 barns sat thermal energies. ^{238}U has a threshold for fission (n, f) at a neutron energy of 1 MeV. This effectively prevents fission from occurring in 238 U. There is very strong resonant capture of neutrons (n, γ) for energies in the range 10-100 eV - particularly in the case of 238U where the cross-section reaches very high values.

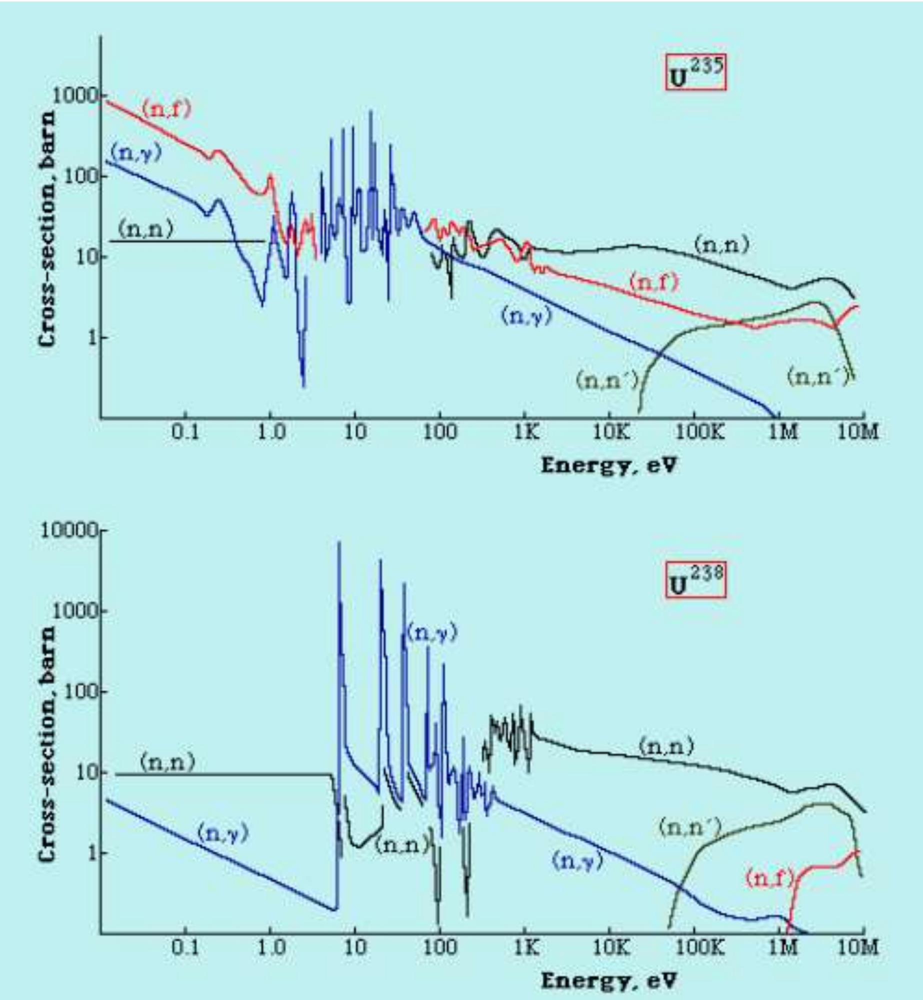


Figure-7: Shows the cross sections for neutron-induced fission of ^{235}U and ^{238}U.

(5) Energy in Fission

Here we described detail the energy involved in fission. When ^{235}U captures a neutron to form the compound state $^{236}U^*$, the excitation energy is

$E_{ex} = [m\,(^{236}U^*) - m\,(^{236}U)]\,c^2 = 931.50$ MeV/u = 6.5 MeV

On the otherhand the activation energy (The energy needed to overcome the fission barrier as in Figure-8) for ^{236}U is calculated also to be 6.2. So, the energy needed to excited ^{236}U into a fissionable state (the activation energy) is exceeded by the energy we get by adding a neutron to ^{235}U. This means that ^{235}U can be fissioned with zero-energy neutrons, consistent with its large observed fission cross section in the thermal region.

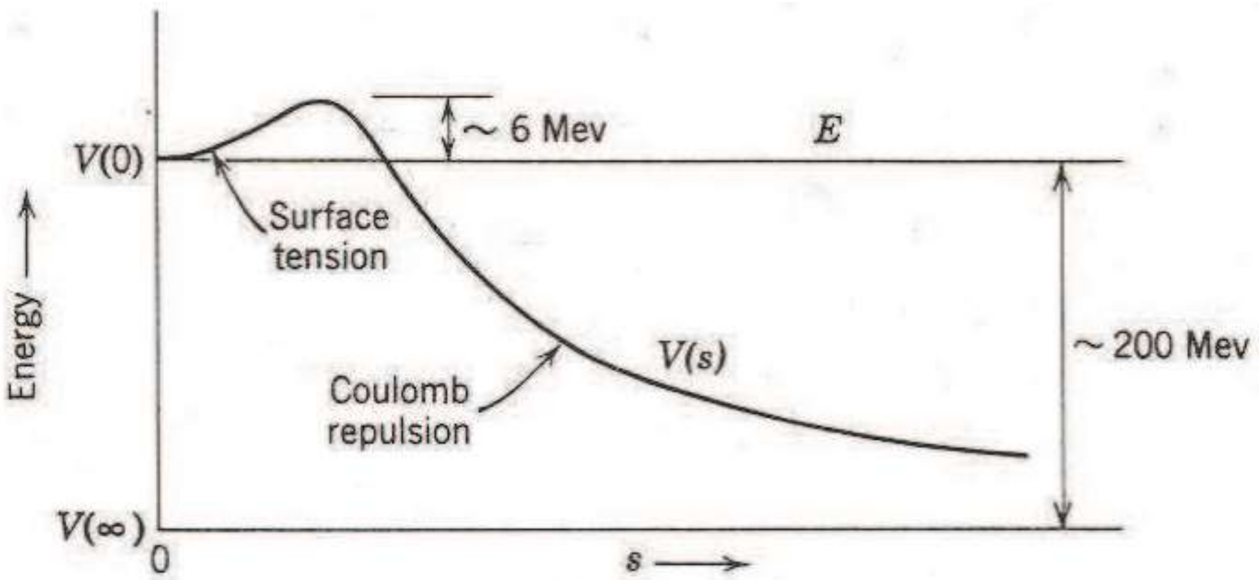


Figure-8: In its deformed state there are two forces acting on the nucleus. One is an increased surface energy and the other is the Coulomb repulsion between the fission fragments. Together these produce a potential barrier.

Binding Energy is energy required to break up an atom or nucleus. Mass of a nucleus is less than the mass of its constituent nucleons (protons and neutrons). If this loss of mass is **m** then an energy

$\mathbf{E = mc^2}$ is released. Most of the energy radiated by stars has been released by nuclear reactions in stellar interiors. Binding energy for a nucleus $^{A}{}_{Z}X$ is

$$Q\,(Z,N)=[Zm_p + Nm_n - m(^{A}{}_{Z}X)]c^2$$

Fission of heavy elements is an exothermic reaction which can release a large amount of energy (~1 MeV per nucleon) both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). In order that fission produces energy, the total binding energy of the resulting elements must be larger than that of the starting element. Fission is a form of nuclear transmutation because the resulting fragments are not the same elements as the original one. Typical fission events release about two hundred million eV (200 MeV) of energy for each fission event, e.g. for ^{235}U: ~235 MeV. By contrast, most chemical oxidation reactions (such as burning coal) release at most a few eV per event. So nuclear fuel contains at least ten million times more usable energy per unit mass than chemical fuel as example: 1 gram of ^{235}U is equivalent to 1 ton of coal (=> 3.5 ton CO_2)!

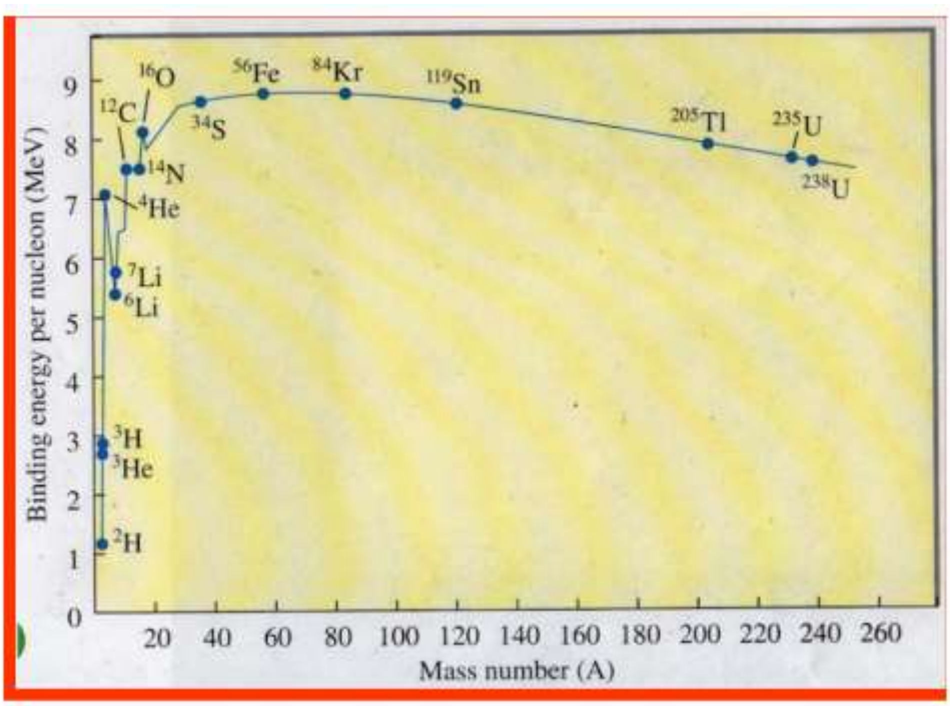


Figure-9: Binding Energy

Controlled Fission Reactions

Nuclear power plants work by controlling the rate of the nuclear reactions, and that control is maintained through several safety measures. The materials in a nuclear reactor core and the uranium enrichment level make a nuclear explosion impossible, even if all safety measures failed.

On the other hand, nuclear weapons are engineered to produce a reaction that is so fast and intense it cannot be controlled after it has started. When properly designed, this uncontrolled reaction can lead to an explosive energy release.

In a nuclear fission reaction in a nuclear power plant, the radioactive element Uranium is used in a chain reaction. The fission of splits off two neutrons, which in turn strike two atoms.

Two neutrons are split from each of the two atoms. Each of these neutrons then go on to strike another atom. Each of those atoms are split releasing two neutrons, which go on and hit more Uranium atoms. The chain reaction continues on and on, getting bigger and bigger with each split.

The things that slow down a chain reaction are the control rods. A control rod is made up of cadmium or boron, which absorb neutrons. If you insert the control rod between the uranium atoms, the amount of neutrons available to cause more splits is reduced.

Nuclear power plants operate by precisely controlling the rate at which nuclear reactions occur, and that control is maintained through the use of several redundant layers of safety measures. Moreover, the materials in a nuclear reactor core and the uranium enrichment level make a nuclear explosion impossible, even if all safety measures failed.

The effective neutron multiplication factor, k, is the average number of neutrons from one fission that causes fission:

k = (Number of Neutrons in one generation)/ (Number of neutrons in preceding generation)

The remaining neutrons either are absorbed in non-fission reactions or leave the system

without being absorbed.

The value of k determines how a nuclear chain reaction proceeds:

- $k < 1$ (subcriticality): The system cannot sustain a chain reaction, and any beginning of a chain reaction dies out in time. For every fission that is induced in the system, an average total of $1/(1 - k)$ fissions occur.

- k = 1 (criticality): Every fission causes an average of one more fission, leading to a fission (and power) level that is constant. Nuclear power plants operate with k = 1 unless the power level is being increased or decreased.
- k > 1 (supercriticality): For every fission in the material, it is likely that there will be k fissions after the next mean generation time. The result is that the number of fission reactions increases exponentially, according to the equation $e^{(k-1)t/\Lambda}$, where t is the elapsed time. Nuclear weapons are designed to operate in this state.

To operate reactor:

- Most of the time we want *k*= 1 to keep power steady.
- To reduce power, or shut the reactor down, we need ways to make *k*< 1:

  done by inserting neutron absorbers, e.g. water, cadmium, boron, gadolinium.
- To increase power, we need to make *k* slightly > 1 for a short time: usually done by removing a bit of absorption.
- In a reactor, we don't want to make *k* much greater than 1, or > 1 for long time, or power could increase to high values, potentially with undesirable consequences, e.g. melting of the fuel.
- Even when we want to keep *k* = 1, we need reactivity devices to counteract perturbations to the chain reaction. The movement of reactivity devices allows absorption to be added or removed in order to manipulate *k*.
- Every nuclear reactor contains regulating and shutdown systems to do the job of keeping *k* steady or increasing or decreasing it, as desired.

Now we can realize two steps as follows:

1) Consider an idealized case – an infinite nuclear medium:

k => neutron multiplication factor in an infinite medium k_∞

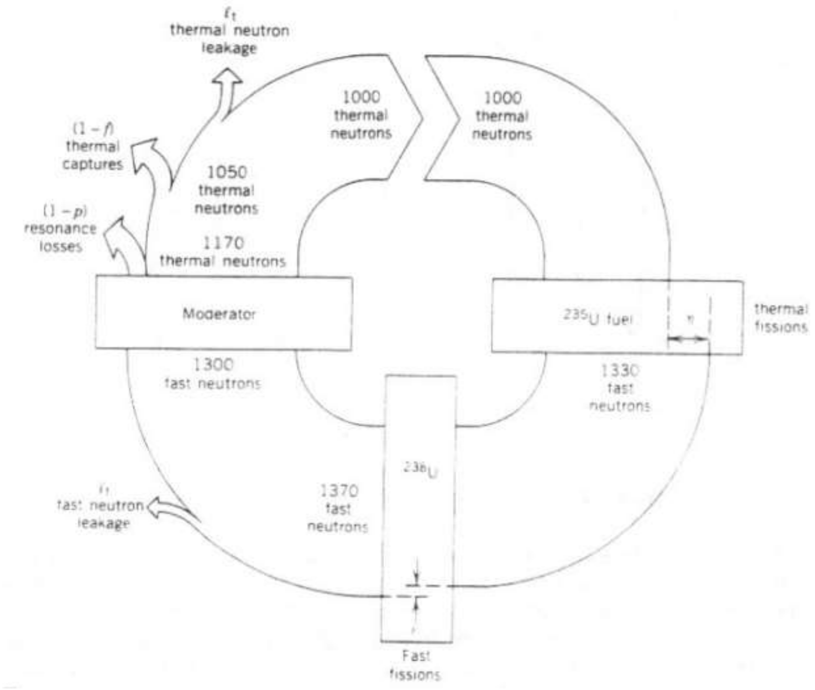
$$k_\infty=\eta f p \varepsilon$$

which known for obvious reasons as the four factor formula. The figure- 10 shows the processes that can occur to neutrons during a reactor cycle.

η- reproduction factor - the number of fission neutrons produced per absorption in the fuel f - the thermal utilization factor - probability that a neutron that gets absorbed does so in the fuel material

p - the resonance escape probability - fraction of fission neutrons that manage to slow down from fission to thermal energies without being absorbed

ε- the fast fission factor = (Total Number of fission neutrons)/(Number of fission neutrons from just thermal fission)



The Figure-10: The processes that can occur to neutrons during a reactor cycle.

2) For the final size medium (as a reactor zone) the neutron will escape from the reaction zone =>

$$k = k_{\infty}P$$

P is a probability for neutrons to stay in the reaction zone – depends on the interia of the reaction zone, geometrical form of reaction zone and surrounding material

Now

ν–average number of neutrons per one fission event

η - reproduction factor -the number of fission neutrons produced per absorption in the fuel

Possible reactions with neutrons:

• Fission reactions (n,f) –cross section σ_{nf}

• Radioactive capture (n,γ) -cross section $\sigma_{n\gamma}$

$$\eta = \nu \frac{\sigma_{nf}}{\sigma_{nf} + \sigma_{n\gamma}}$$

The chain reactions are possible only if η>1, η depends on the quality of the fuel: the larger η the better is the fuel

Fuel Use in the Reactor

Radioactive capture of neutrons by ^{238}U or ^{233}Th decreases the efficiency of the chain reactions, however, leads to the manufacturing of fuel, i.e. the production of 233U and ^{239}Pu :

$$n + {}^{238}_{92}U \longrightarrow {}^{239}_{92}U \xrightarrow[\beta^-,23min]{} {}^{239}_{93}Np \xrightarrow[\beta^-,2,3days]{} {}^{239}_{94}Pu$$

$$n + {}^{232}_{90}Th \longrightarrow {}^{233}_{90}Th \xrightarrow[\beta^-,22min]{} {}^{233}_{91}Pa \xrightarrow[\beta^-,27days]{} {}^{233}_{92}U$$

In nature there are only 3 isotopes - ^{235}U, ^{238}U and ^{232}Th –which can be used as nuclear fuel (^{235}U) or reproduction of fuel (as $^{238}U \rightarrow$239Pu; $^{232}Th \rightarrow {}^{233}U$). Naturally occurring uranium consists 99.3% of ^{238}U and only 0.7% of ^{235}U i.e. for 1 nucleus of ^{235}U there are 140 nuclei of ^{238}U.

In order to use the naturally occurring uranium as a nuclear fuel, one needs to slow down the fast neutrons to thermal energies

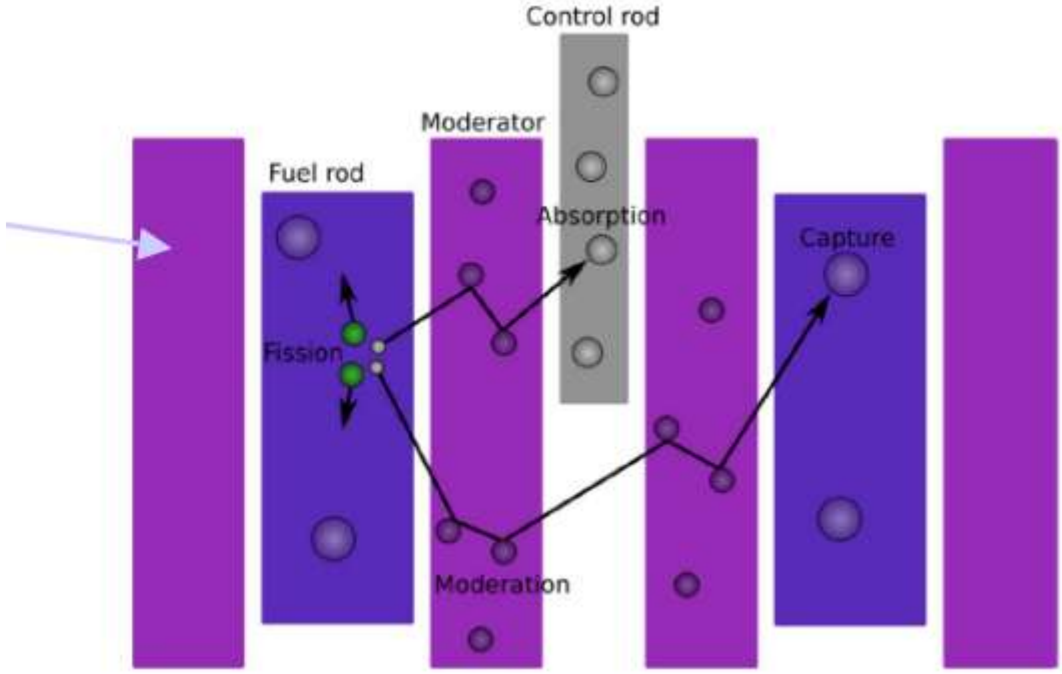


Figure-11: Fuel Rod

Moderator

In nuclear reactors there are neutron moderators, which reduce the velocity of fast neutrons, thereby turning them into thermal neutrons.

Moderators are compounds containing light nuclides such as H, D, He, C, O, F. Materials with low neutron-capture cross section are desirable. The following substances are commonly used as moderators.

- graphite,
- H_2O, D_2O
- He (100 Atm and 1273 K)
- Be (high temperature liquid metal).
- Na (773 to 873 K used in breeder reactor)
- BeF_2 + ZrF_4 (for GCR)

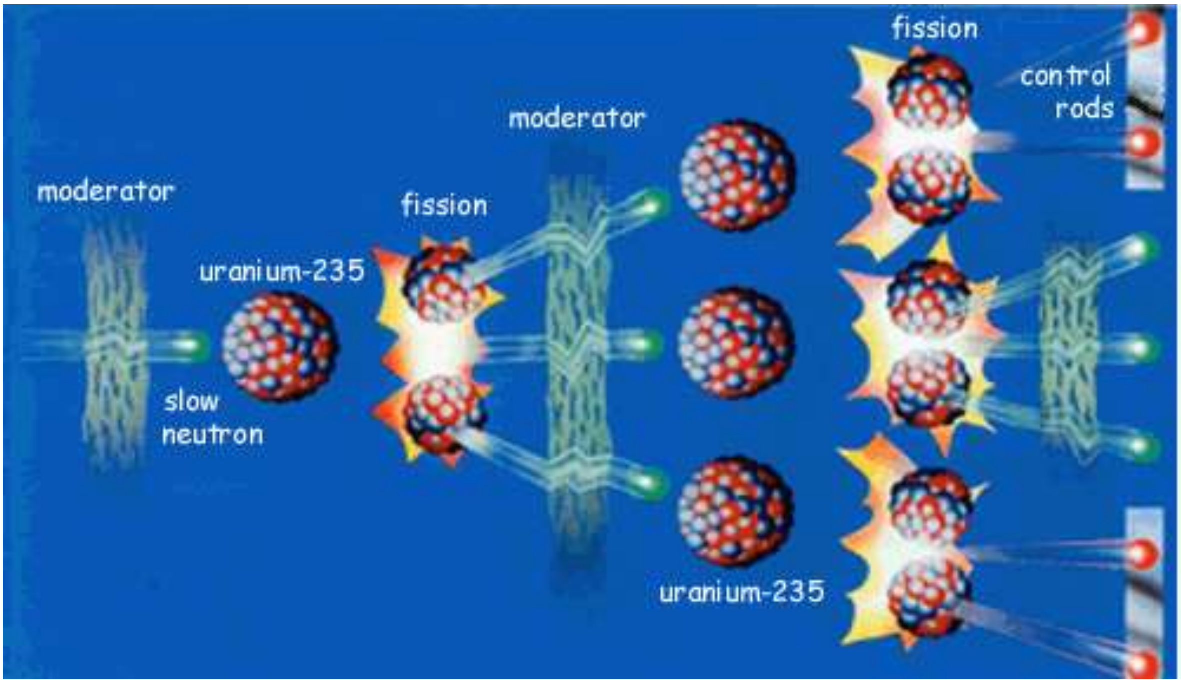


Figure-12: Moderator

Absorber

A control rod is a rod made of chemical elements capable of **absorbing** many neutrons without fissioning themselves. They are used in nuclear reactors to control the rate of fission of uranium and plutonium. Because these elements have different capture cross sections for neutrons of varying energies, the compositions of the control rods must be designed for the neutron spectrum of the reactor it is supposed to control. Light water reactors (BWR, PWR) and heavy water reactors (HWR) operate with "thermal" neutrons, whereas breeder reactors operate with "fast" neutrons.

Usually, Cadmium, Boron, Carbon, Cobalt, Silver, Hafnium, Gadolinium and Europium are common elements used in control rods.

Technology of Nuclear Power Plants

Nuclear Power Plant

In a nuclear power plant use is made of the fission reaction. Most power plants produce electricity by first boiling water to produce steam. The steam is used to spin a turbine. The shaft of the turbine spins the generator (a large coil of wire) between two magnets. The spinning coil of wire generates electricity by electromagnetic induction.

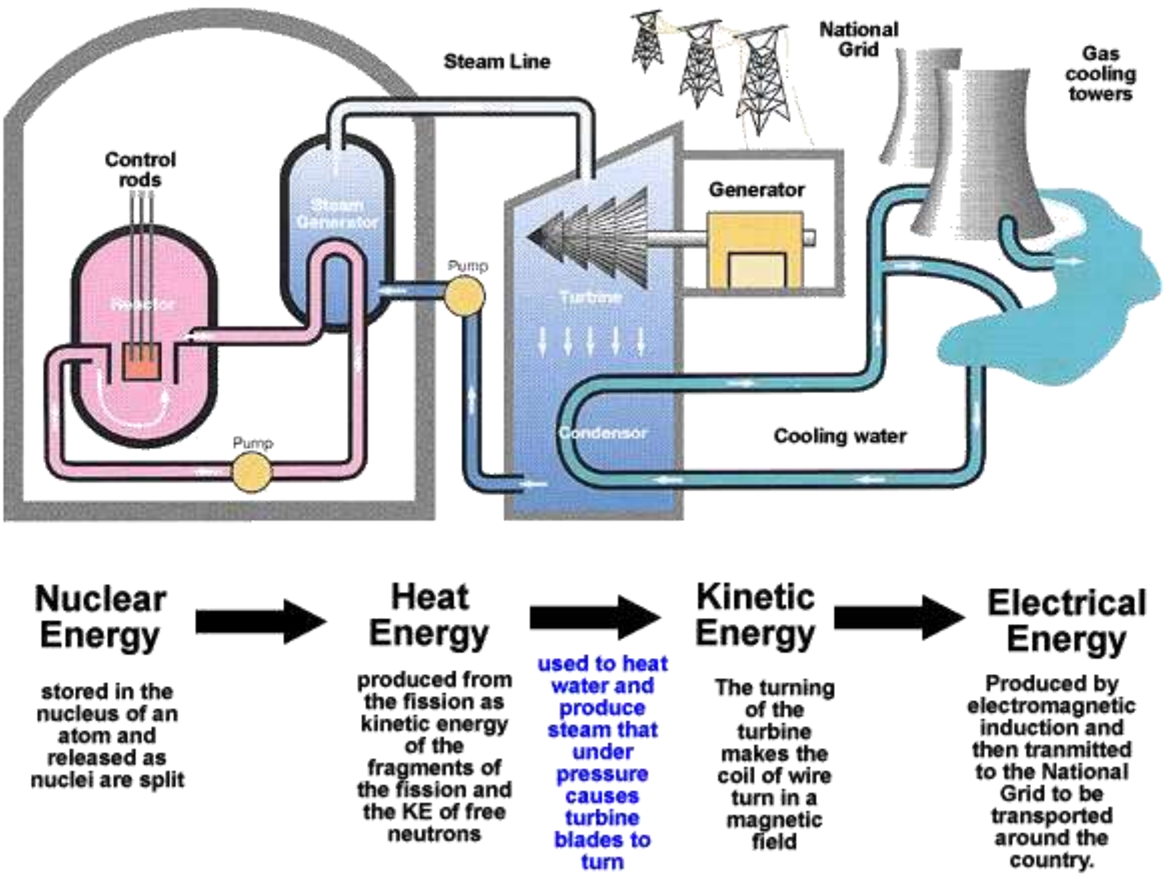


Figure-13: Nuclear Power Plant

The main difference between a nuclear power plant and other kinds of power plants lies in the way the water is heated to steam. In a nuclear power plant, heat is produced by nuclear fission - splitting atoms - rather than, for example, the combustion of oil, gas, or coal.

A nuclear reactor is a device in which nuclear chain reactions are initiated, controlled, and sustained at a steady rate. The heat produced is carried away by a heat exchange system and then turned into electrical energy via a generator system.

A nuclear power plant (NPP) is a thermal power station in which the heat source is one or more nuclear reactors.

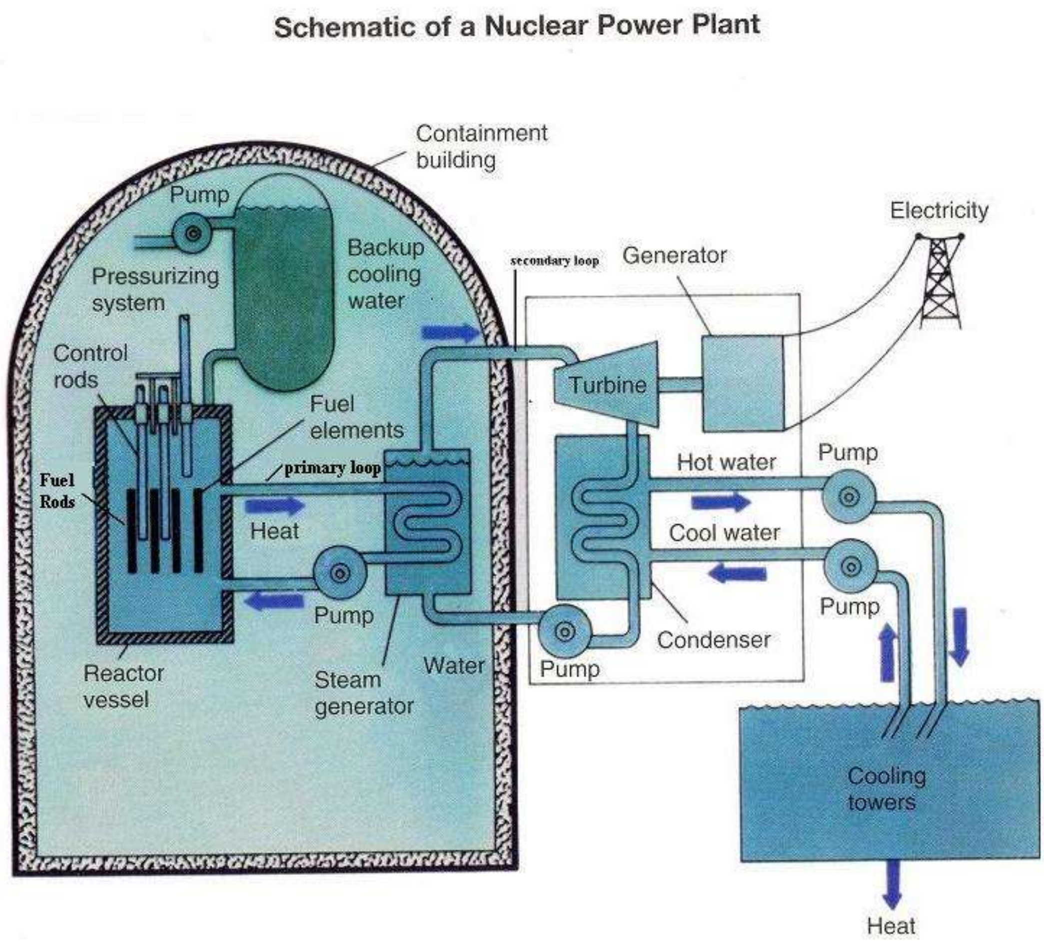


Figure-14: Schematic of a Nuclear Power Plant

The schematic arrangement of a nuclear power station is shown above. The whole arrangement can be divided into following main stages.

(i)Nuclear Reactor (ii) Heat Exchanger (iii) Steam Turbine (iv) Alternator

Nuclear Reactor

It is an apparatus in which nuclear fuel (^{235}U) is subjected to nuclear fission. It controls the chain reaction that starts once the fusion is done. If the chain reaction is not controlled, the result will be an explosion due to the fast increase in the energy released.

A nuclear reactor is a cylindrical stout pressure vessel and houses fuel rods of Uranium moderator and control rods. The fuel rods constitute the fission materials and release huge amount of energy when bombarded with slow moving neutrons. The moderator consists of graphite rods which enclose the fuel rods. The control rods are of Cadmium and are inserted in the reactor. Cadmium is strong neutron absorber and thus regulates the supply of neutrons for fission. When the control rods are pushed in deep enough, they absorb most of fission neutrons and hence few are available for chain reaction, which therefore stops. However, hence they are being withdrawn, more and more of these fission neutrons cause fission and hence the intensity of chain reaction is increased. Therefore by pulling out the control rods, power of nuclear reactor is increased, whereas by pushing them in, it is reduced. In actual practice, the lowering or raising of control rods is accomplished automatically according to the requirement of load. The heat produced by the reactor is removed by the coolant, generally a sodium metal. The coolant carries heat to the heat exchanger.

Heat Exchanger

The coolant gives up the heat to the heat exchanger which is utilized in raising the steam. After giving up heat, the coolant is again fed to the reactor.

Steam Turbine

The Steam produced in the heat exchanger is led to the steam turbine through a valve. After doing a useful work in the turbine, the steam is exhausted to the condenser. The condensers condense the steam which is fed to the heat exchanger through feed water pump.

Alternator

The steam turbine drives the alternator which converts mechanical energy into electrical energy. The output from the alernator is delivered to the bus bars through transformers, circuit brakers and isolators

Essential Components and types of a Nuclear Reactor

A nuclear reactor is a system that contains and controls sustained nuclear chain reactions. Reactors are used for generating electricity, moving aircraft carriers and submarines, producing medical isotopes for imaging and cancer treatment, and for conducting research.

Fuel, made up of heavy atoms that split when they absorb neutrons, is placed into the reactor vessel (basically a large tank) along with a small neutron source. The neutrons start a chain reaction where each atom that splits releases more neutrons that cause other atoms to split. Each time an atom splits, it releases large amounts of energy in the form of heat. The heat is carried out of the reactor by coolant, which is most commonly just plain water. The coolant heats up and goes off to a turbine to spin a generator or drive shaft. So basically, nuclear reactors are exotic heat sources.

Nuclear reactor is an assembly of fissionable material (uranium-235 or plutonium-239) designed to produce a sustained and controllable chain reaction for the generation of electric power.

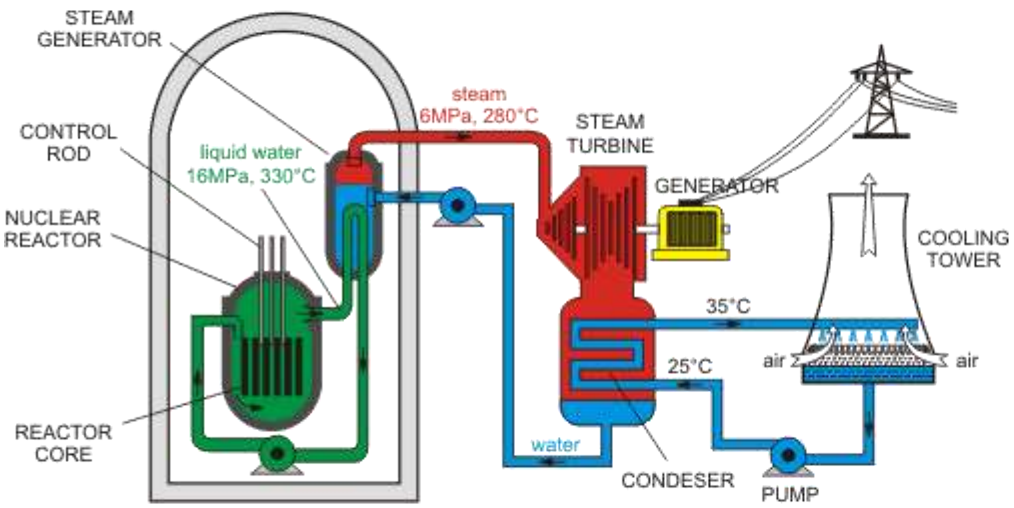


Figure-15: Essential Components of a Nuclear Power Plant

The essential components of a nuclear reactor are:

1. **The core** of the reactor contains all of the nuclear fuel and generates all of the heat. It contains low-**enriched** uranium (<5% U-235), control systems, and structural materials. The core can contain hundreds of thousands of individual fuel pins.
2. **The coolant** is the material that passes through the core, transferring the heat from the fuel to a turbine. It could be water, heavy-water, liquid sodium, helium, or something else. In the US fleet of power reactors, water is the standard.
3. **The turbine** transfers the heat from the coolant to electricity, just like in a fossil-fuel plant.
4. **The containment** is the structure that separates the reactor from the environment. These are usually dome-shaped, made of high-density, steel-reinforced concrete. Chernobyl did not have a containment to speak of.
5. **Cooling towers** are needed by some plants to dump the excess heat that cannot be converted to energy due to the laws of thermodynamics. These are the hyperbolic icons of nuclear energy. They emit only clean water vapor.

Types of Nuclear Reactors

There are very many different types of nuclear reactors with different fuels, coolants, fuel cycles, purposes.

Pressurized Water Reactor

The most common type of reactor -- the PWR uses regular old water as a coolant. The primary cooling water is kept at very high pressure so it does not boil. It goes through a heat exchanger, transferring heat to a secondary coolant loop, which then spins the turbine. These use oxide fuel pellets stacked in zirconium tubes. They could possibly burn thorium or plutonium fuel as well.

Properties:

(1) Strong negative void coefficient -- reactor cools down if water starts bubbling because the coolant is the **moderator**, which is required to sustain the chain reaction
(2) Secondary loop keeps **radioactive** stuff away from turbines, making maintenance easy.
(3) Very much operating experience has been accumulated and the designs and procedures have been largely optimized.

Construction:

- Pressurized coolant escapes rapidly if a pipe breaks, necessitating lots of back-up cooling systems.
- Can't **breed new fuel** -- susceptible to "uranium shortage"

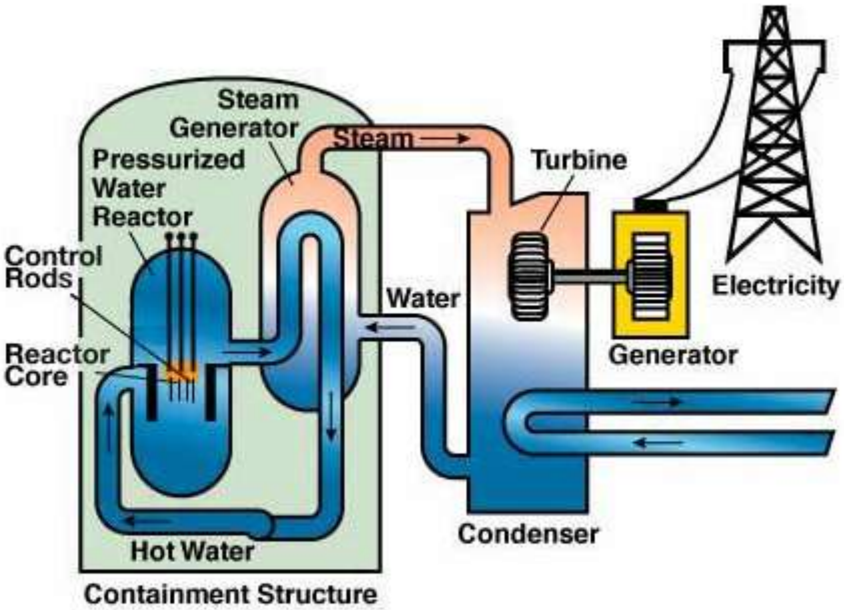


Figure-16: Pressurized Water Reactor

Boiling Water Reactor

Second most common, the BWR is similar to the PWR in many ways. However, they only have one coolant loop. The hot nuclear fuel boils water as it goes out the top of the reactor, where the steam heads over to the turbine to spin it.

Properties:

(1) Simpler plumbing reduces costs

(2) Power levels can be increased simply by speeding up the jet pumps, giving less boiled water and more moderation. Thus, load-following is simple and easy.

(3) Very much operating experience has been accumulated and the designs and procedures have been largely optimized.

Construction:

● With liquid and gaseous water in the system, many weird transients are possible, making safety analysis difficult

● Primary coolant is in direct contact with turbines, so if a fuel rod had a leak, radioactive material could be placed on the turbine. This complicates maintenance as the staff must be dressed for radioactive environments.

● Can’t breed new fuel -- susceptible to "uranium shortage"

● Does not typically perform well in station blackout events, as in Fukushima.

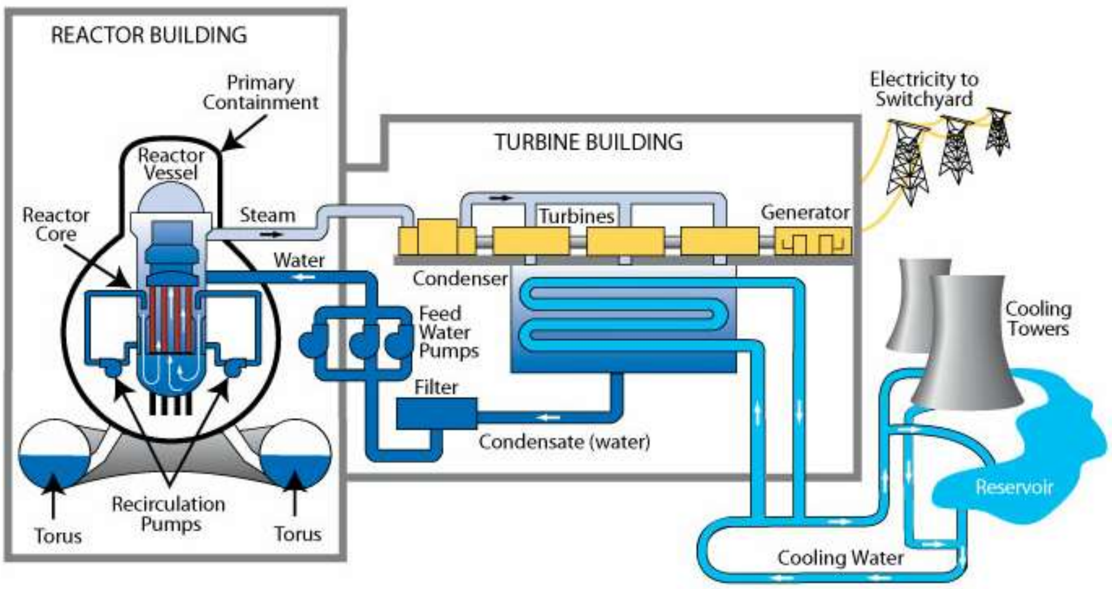


Figure-17: Boiling Water Reactor

Sodium Cooled Fast Reactor

The first electricity-producing nuclear reactor in the world was SFR (the EBR-1 in Arco, Idaho). As the name implies, these reactors are cooled by liquid sodium metal. Sodium is heavier than hydrogen, a fact that leads to the neutrons moving around at higher speeds (hence fast). These can use metal or oxide fuel, and burn anything you throw at them (thorium, uranium, plutonium, higher actinides).

Properties:

(1) Can breed its own fuel, effectively eliminating any concerns about uranium shortages
(2) Can burn its own waste
(3) Metallic fuel and excellent thermal properties of sodium allow for passively safe operation -- the reactor will shut itself down and cool **decay heat** without any backup-systems working (or people around), only relying on physics (gravity, natural circulation, etc.).

Construction:

● Sodium coolant is reactive with air and water. Thus, leaks in the pipes results in sodium fires. These can be engineered around (by making a pool and eliminating pipes, etc.) but are a major setback for these nice reactors.

● To fully burn waste, these require reprocessing facilities which can also be used for nuclear proliferation.

● The excess neutrons used to give the reactor its resource-utilization capabilities could clandestinely be used to make plutonium for weapons.

● Positive void coefficients are inherent to most fast reactors, especially large ones. This is a safety concern.

● Not as much operating experience has been accumulated

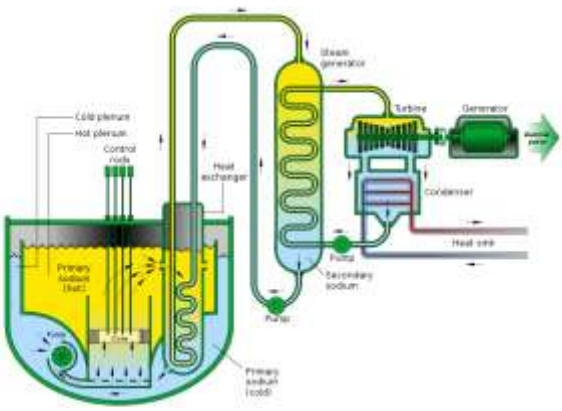


Figure-18: Sodium Cooled Fast Reactor

Canada Deuterium-Uranium Reactors (CANDU)

CANDUs are a Canadian design found in Canada and around the world. They contain heavy water, where the Hydrogen in H2O has an extra neutron (making it Deuterium instead of Hydrogen). Deuterium absorbs many fewer neutrons than Hydrogen, and CANDUs can operate using only natural uranium instead of enriched.

Properties:

(1) Require very little uranium **enrichment**.
(2) Can be refueled while operating, keeping capacity factors high (as long as the fuel handling machines don't break).
(3) Are very flexible, and can use any type of fuel.

Construction:

● Some variants have positive coolant temperature coefficients, leading to safety concerns.

● Neutron absorption in deuterium leads to tritium production, which is radioactive and often leaks in small quantities.

● Can theoretically be modified to produce weapons-grade plutonium slightly faster than conventional reactors could be.

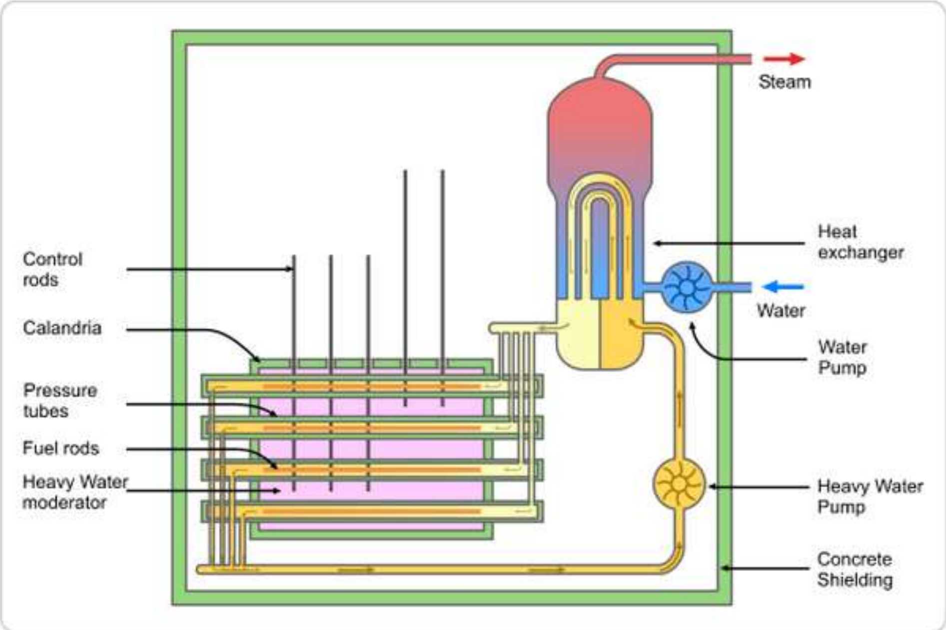


Figure-19: Canada Deuterium-Uranium Reactors (CANDU)

Liquid Fluoride Thorium Reactor

LFTRs have gotten a lot of attention lately in the media. They are unique so far in that they use molten fuel. So there's no worry of meltdown because they're already melted and the reactor is designed to handle that state. The folks over at **Energy from thorium** are totally stoked about this technology. Properties:

(1) Can constantly **breed new fuel**, eliminating concerns over energy resources

(2) Can be maintained online with chemical fission product removal, eliminating the need to shut down during refueling.

(3) No cladding means less neutron-absorbing material in the core, which leads to better neutron efficiency and thus higher fuel utilization

(4) Liquid fuel also means that structural dose does not limit the life of the fuel, allowing the reactor to extract very much energy out of the loaded fuel.

Construction

● Radioactive gaseous fission products are not contained in small pins, as they are in typical reactors. So if there is a containment breach, all the fission gases can release instead of just the gases from one tiny pin. This necessitates things like triple-redundant containments, etc. and can be handled, but is certainly a challenge and disadvantage. All liquid fuel reactors have this problem.

●The presence of an online reprocessing facility with incoming pre-melted fuel is a **proliferation** concern. The operator could easily divert Pa-233 to provide a small stream of nearly pure weapons-grade U-233. Also, the entire uranium inventory can be separated without much effort. In his autobiography, Alvin Weinberg explains how this was done at Oak Ridge National Lab: "It was a remarkable feat! In only 4 days all of the 218 kg of uranium in the reactor were separated from the intensely radioactive fission products and its radioactivity reduced five billion-fold." Thus, anyone who operates this kind of reactor will have easy access to bomb material.

● Very little operating experience

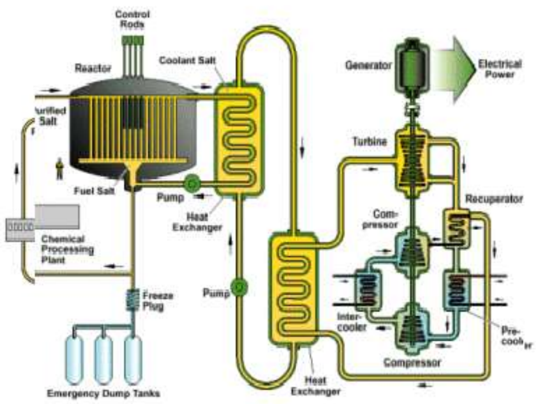


Figure-20: Liquid Fluoride Thorium Reactor

High Temperature Gas Cooled Reactor

HTGRs use little pellets of fuel backed into either hexagonal compacts or into larger pebbles (in the prismatic and pebble-bed designs). Gas such as helium or carbon dioxide is passed through the reactor rapidly to cool it. Due to their low power density, these reactors are seen as promising for using nuclear energy outside of electricity: in transportation, in industry, and in residential regimes. They are not particularly good at just producing electricity.

Properties:

(1) Can operate at very high temperatures, leading to great thermal efficiency (near 50%) and the ability to create process heat for things like oil refineries, water desalination plants, hydrogen fuel cell production, and much more.

(2) Each little pebble of fuel has its own containment structure, adding yet another barrier between radioactive material and the environment.

Construction:

- High temperature has a bad side too. Materials that can stay structurally sound in high temperatures and with many neutrons flying through them are hard to come by.
- If the gas stops flowing, the reactor heats up very quickly. Backup cooling systems are necessary.
- Gas is a poor coolant, necessitating large amounts of coolant for relatively small amounts of power.
- Therefore, these reactors must be very large to produce power at the rate of other reactors.
- Not as much operating experience

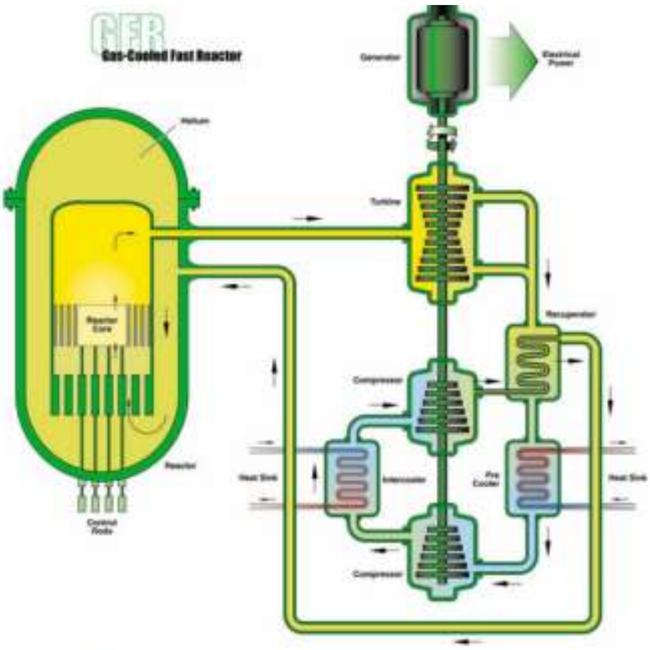


Figure-21: High Temperature Gas Cooled Reactor

How Nuclear Power Plant Works

Now many people are watching wanting to get an update and are curious how exactly a Nuclear Power Plants Works**.**

1. First, uranium fuel is loaded up into the reactor—a giant concrete dome that's reinforced in case it explodes. In the heart of the reactor (the core), atoms split apart and release heat energy, producing neutrons and splitting other atoms in a chain reaction.
2. Control rods made of materials such as cadmium and boron can be raised or lowered into the reactor to soak up neutrons and slow down or speed up the chain reaction.
3. Water is pumped through the reactor to collect the heat energy that the chain reaction produces. It constantly flows around a closed loop linking the reactor with a heat exchanger.
4. Inside the heat exchanger, the water from the reactor gives up its energy to cooler water flowing in another closed loop, turning it into steam. Using two unconnected loops of water and the heat exchanger helps to keep water contaminated with radioactivity safely contained in one place and well away from most of the equipment in the plant.
5. The steam from the heat exchanger is piped to a turbine. As the steam blows past the turbine's vanes, they spin around at high speed.
6. The spinning turbine is connected to an electricity generator and makes that spin too.
7. The generator produces electricity that flows out to the power grid—and to our homes, shops, offices, and factories.

Advantages

- Almost zero emissions (very low greenhouse gas emissions).
- They can be sited almost anywhere unlike oil which is mostly imported.
- The plants almost never experience problems if not from human error, which almost never happens anyway because the plant only needs like 10 people to operate it.
- A small amount of matter creates a large amount of energy.
- A lot of energy is generated from a single power plant.
- Current nuclear waste in the US is over 90% Uranium. If reprocessing were made legal again in the US
- We would have enough nuclear material to last hundreds of years.
- A truckload of Uranium is equivalent in energy to 10,000+ truckloads of coal. (Assuming the Uranium is fully utilized.)
- A nuclear aircraft carrier can circle the globe continuously for 30 years on its original fuel while a diesel fueled carrier has a range of only about 3000 miles before having to refuel.
- New reactor types have been designed to make it physically impossible to melt down. As the core gets

hotter the reaction gets slower, hence a run-away reaction leading to a melt-down is not possible.

● Theoretical reactors (traveling wave) are proposed to completely eliminate any long-lived nuclear waste created from the process.

● Breeder reactors create more usable fuel than they use.

● Theoretical Thorium reactors have many of the benefits of Uranium reactors while removing much of the risk for proliferation as it is impossible to get weapons-grade nuclear materials from Thorium.

Disadvantages

● Nuclear plants are more expensive to build and maintain.

● Proliferation concerns - breeder reactors yield products that could potentially be stolen and turned into an atomic weapon.

● A lot of waste from early reactors was stored in containers meant for only a few decades, but is well past expiration and, resultingly, leaks are furthering contamination.

● Nuclear power plants can be dangerous to its surroundings and employees. It would cost a lot to clean in case of spillages.

● There exist safety concerns if the plant is not operated correctly or conditions arise that were unforeseen when the plant was developed, as happened at the Fukushima plant in Japan; the core melted down following an earthquake and tsunami the plant was not designed to handle despite the world's strongest earthquake codes.

● Mishaps at nuclear plants can render hundreds of square miles of land uninhabitable and unsuitable for any use for years, decades or longer, and kill off entire river systems

Conclusions

Nuclear power is a clean, safe, affordable way to meet future power demands in the all around the world. It emits virtually no greenhouse gases (GHG), making it a clean power source that can help address global warming.

Nuclear power plants can produce an uninterrupted flow of electricity for extended periods. This uninterrupted flow supplies the necessary level of base load electricity for the grid to operate around the clock.

To establish a nuclear power plant, we have to take more cautious for the following important issues:

Environmental Impacts:

Perhaps the impact which is easiest to notice is the effect on the environment. To start with, the setting up of a nuclear plant requires a large area, preferably situated near a natural water body. This is usually accompanied with clearing of forests which disturbs the natural habitat of several creatures and gradually upsets the ecological balance of the region. Apart from this, studies have shown that due to the heat rejected into the water bodies, there have been significant drops in the populations of several species of fish in certain regions of the world. Another significant effect is the increased amount of sulfur dioxide in the air which causes acid rain to form which then leads to contamination of surface water bodies of the region, reduction of productivity of the soil, and has several other negative effects on the region's vegetation and human health.

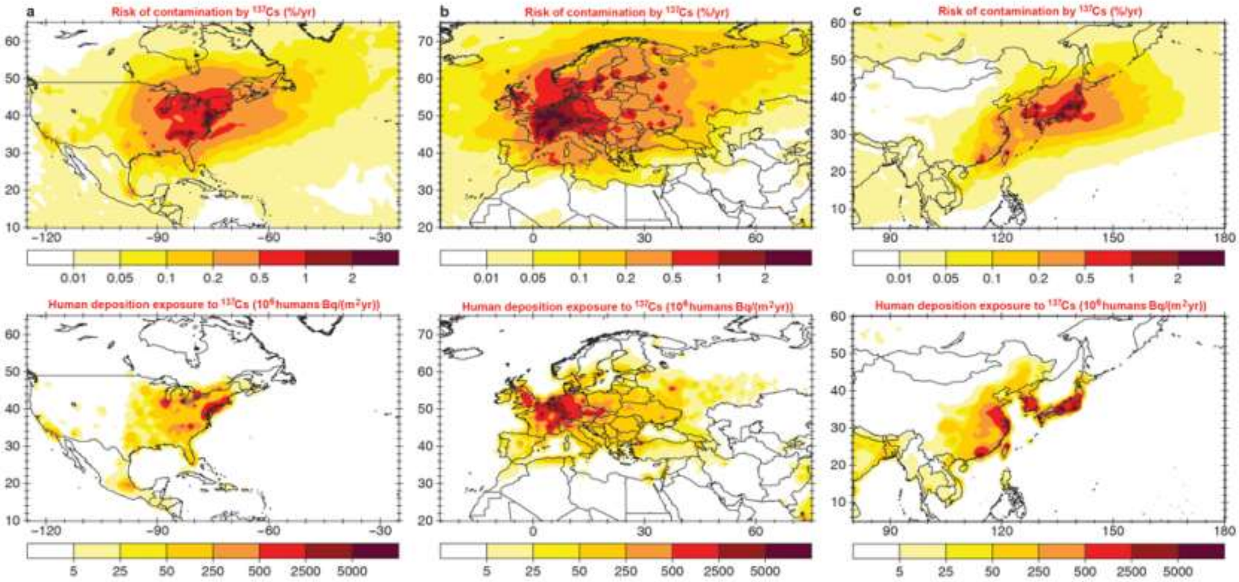


Figure-22. Regional risks of radioactive contamination by 137Cs

Waste Management's:

Low and intermediate level radioactive waste (LILW) at nuclear power plants is produced by contamination of various materials with the radionuclides generated by fission and activation in the reactor or released from the fuel or cladding surfaces. The radionuclides are primarily released and collected in the reactor coolant system and, to a lesser extent, in the spent fuel storage pool. The main wastes arising during the operation of a nuclear power plant are components which are removed during refueling or maintenance (mainly activated solids, e.g. stainless steel containing cobalt-60 and nickel-63) or operational wastes such as radioactive liquids, filters, and ion-exchange resins which are contaminated with fission products from circuits containing liquid coolant. In order to reduce the quantities of waste for interim storage and to minimize disposal cost, all countries are pursuing or intend to implement measures to reduce the volume of waste arising where practicable. Volume reduction is particularly attractive for low-level waste which is generally of high volume but low radiation activity. Significant improvements can be made through administrative measures, e.g. replacement of paper towels by hot air driers, introduction of reusable long-lasting protective clothing, etc., and through general improvements of operational implementation or "housekeeping". When uranium has completed the fission process, nuclear waste is formed that takes thousands of years to disappear. That waste needs to be stored somewhere that won't harm the environment

Accidents:

Like any large scale industrial activity, there have been numerous accidents and mistakes at Nuclear Power plants and reprocessing facilities.

However two large accidents have had the greatest impact on global consciousness regarding Nuclear Power. These are:

- Three Mile Island in 1979.
- Chernobyl in 1986.

The following table shows the accidents occurred from the very beginning of the Nuclear Power Plants:

Location	Country	INES	Date	Total	^{131}I	^{137}Cs
Fukushima	Japan	7	11 March 2011	>630	190–380	12–37
Chernobyl	USSR	7	26 April 1986	>12 000	1760	85
Mayak	USSR	6	29 September 1957	74–1850	n.d.a	n.d.a
Chalk River	Canada	5	12 December 1952	>0.3	n.d.a.	n.d.a.
Windscale	UK	5	10 October 1957	1.6	0.7	0.02
Simi Valley	USA	5–6	26 July 1959	> 200[a]	b	n.d.a.
Belojarsk	USSR	5	1977	n.d.a.	n.d.a.	n.d.a.
Three Mile Island	USA	5	28 March 1979	1.6[c]	<0.0007	n.d.a.
Chernobyl	USSR	5	1 September 1982	n.d.a.	n.d.a.	n.d.a.
Idaho Falls	USA	4	29 November 1955	d	d	d
Idaho Falls	USA	4	3 January 1961	n.d.a.	n.d.a.	n.d.a.
Monroe	USA	4	5 October 1966	d	d	d
Lucens	Switzerland	4–5	21 January 1969	d	d	d
Windscale	UK	4	1973	n.d.a.	n.d.a.	n.d.a.
Leningrad	USSR	4–5	6 February 1974	e	n.d.a.	n.d.a.
Leningrad	USSR	4–5	October 1974	55	n.d.a.	n.d.a.
Jaslovské Bohunice	CSSR	4	22 February 1977	n.d.a.	n.d.a.	n.d.a.
Saint-Laurent	France	4	13 March 1980	n.d.a.	n.d.a.	n.d.a.
Buenos Aires	Argentina	4	23 September 1983	n.d.a.	b	n.d.a.
Tokaimura	Japan	4	30 September 1999	n.d.a.	n.d.a.	n.d.a.

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