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Nuclear Energy: An Overview

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Abstract

Nuclear energy is the way of the future. It is definitely economical. The only question has to do with the environment and the destruction of human cells of the workers giving them cancer and other unpalatable maladies: skin burns, blood conditions etc. A little mass of uranium gives rise to much energy: the loss of one gram of matter in Einstein's equation releases energy sufficient to heat about 200 tonnes of water from 0 ^{o}C to 100 ^{o}C. Running a nuclear energy programme contends with the risk of radiation, accident, waste management , nuclear weapon proliferation, inadequate technology, negative and frightful politics, weak and inefficient government e.g in the third world. For all that, Fast Breeder Reactors seem to hold the promise of consuming present day nuclear waste stockpiles of U-238 while also meeting the world's energy demands.

Keywords: energy, fission, fusion, reactor, moderator, isotope, breeder reactor, fast reactor, chain reaction, half life, radioactive decay, nuclear waste.

1. Introduction

Uranium is a lustrous, white metal with a bluish tint, capable of taking a high polish. It is a very heavy metal, having a specific gravity of 18.7. Pure Uranium is both malleable and ductile, and commercially it can be cast and then fabricated by rolling or extrusion, followed by drawing. It is a chemically reactive metal and oxidizes at moderately high temperatures. Consequently, it must be protected during fabrication processes. For atomic energy purposes it is usually vacuum melted in high-frequency furnaces, and cast in 25 mm diameter rods.

Chemically, uranium is similar to tungsten or molybdenum. Like them, it forms stable carbides which led to the experimental use of uranium in high-speed steels. These steels have not survived, since they showed no advantage over orthodox alloys.

Uranium is one of a number of alloys that undergo natural radioactive disintegration. During such spontaneous disintegration three different types of emission proceed from the source-the so called α, β and γ-`rays'. The phenomenon generally referred to as α-rays is in fact the effect produced by a stream of moving particles-α-particles. An α-particle is, in effect, of the same constitution as the nucleus of a helium atom. Similarly, β-rays consist of a stream of fast moving β-particles (in actual fact these are electrons). Only γ-rays are true electromagnetic radiation and since this radiation is of short wavelength it is able to penetrate considerable thicknesses of metal, (Higgins R.A. 1989).

All three forms of radiation are emitted at some stage in the natural radioactive disintegration of uranium, ^{238}U. Obviously the loss of an α-particle from the nucleus of a ^{238}U atom will cause a change in both its atomic mass and atomic number and consequently in its properties. In this general way ^{238}U changes in a series of steps to radium, and finally to a stable, non-radioactive isotope of lead ^{206}Pb. Each stage of the radioactive decay is accompanied by the emission of one or more of the types of radiation described above. Figure 1 is simplified representation of this process.

Some stages in the process of radioactive disintegration take place more quickly than others, and each separate decay process is governed by the expression:-

$$-\frac{dn}{dt} = \lambda n \qquad (1)$$

Where n is the number of atoms of the species present and λ a constant for that species. Integration of this expression and evaluation of the time necessary for half of the atoms present, initially, to decompose gives what is called the half life of the species. (Higgins R.A. 1989; McMullan J.T. 1977;Sekimoto H 2007).

Thus:

$$t_{½}=\frac{0.6932}{\lambda} \qquad (2)$$

Each radioactive species is characterized by its half life period. Thus it takes 4.5x10^9 years for half of the ^{238}U atoms present in a mass of uranium to change to the next uranium isotope in the series, whilst it takes only 1590 years for half of the radium atoms present to change to the radioactive gas radon.

Until its development as a source of fissionable material, uranium was little more than a chemical and metallurgical curiosity so that, before 1943, there was no commercial extraction process operating with the object of uranium as the sole product. Its industrial use, before the Second World War, was limited to the manufacture of electrodes for gas-discharge tubes; whilst its compounds were used in the manufacture of incandescent gas mantles.

The reader will, no doubt, associate uranium with the production of nuclear power. This element has two principle isotopes, the atoms of which contain 92 protons and 92 electrons in each case. However, one isotope has 146 neutrons giving a total mass of 238, whilst the other has 143 neutrons giving a total mass of 235. These isotopes are generally represented by the symbols ${}^{238}_{92}U$ and ${}^{235}_{92}U$ respectively. Here the lower index represents the number of protons (92) in the nucleus (*the atomic number Z)* and the upper index represents the total number of protons and neutrons (*the atomic mass, A*, of the isotope).

Since a neutron has no electrical charge, and hence suffers neither attraction nor repulsion by either the positively charged protons or the negatively charged electrons, it can be fired into the nucleus of an atom. When an atom enters the nucleus of an atom of ${}^{235}_{92}U$, the latter becomes unstable and splits into two approximately equal portions. At the same time a small reduction in the total mass occurs for although the total number of particles (protons and neutrons) remains the same after fission, the sum of the masses of the resulting nuclei is slightly less. This is a measure of the *mass* equivalent of the nuclear binding *energy*. Einstein's Theory of Relativity states that mass and energy are not distinct entities but are really different manifestations of the same thing. The two are related to the velocity of light (c) by the expression:

$$E=mc^2 \qquad (3)$$

Since the velocity of light is 2.998 x10^8 m/s it follows (Higgins R.A, 1989) that even a small loss in mass can result in a great release of energy. As is often the case in engineering problems, this energy is emitted in the form of heat. It can be calculated that the energy produced by the loss of one gram of matter in this way is sufficient to heat about 200 tonnes of water from 0 °C to 100 °C.

Fission is also accompanied by the emission of neutrons and if the overall mass of ${}^{235}_{92}U$ is great enough, other atoms will absorb some of these neutrons so that a chain reaction occurs leading to an atomic `explosion'. There is a `critical size' for a mass of ${}^{235}_{92}U$. Below this critical size neutrons will tend to escape rather than be absorbed by ${}^{235}_{92}U$ nuclei, and a chain reaction will not, therefore, be promoted.

The rate of production of nuclear energy from this source can be controlled by introducing into an `atomic pile' rods of some element which will absorb unwanted neutrons and thus control the rate of disintegration of other ${}^{235}_{92}U$ atoms. In natural uranium total disintegration will not occur since only 0.7% ${}^{235}_{92}U$ is present, mixed with the more common isotope ${}^{238}_{92}U$. Isotope ${}^{238}_{92}U$ will however, absorb a neutron to give an atom of nuclear mass 239. This undergoes further change to produce plutonium, ${}^{239}_{94}U$, which can be used as a concentrated fuel in such `fast reactors' as that at Dounreay. (Higgins R.A. 1989).

2. Nuclear Reactors

Each fission in ${}^{235}_{92}U$ releases 200 MeV of energy. Since 1 MeV=1.6x10^{-13} Ws we see that each fission frees 3.2x10^{-11}Ws and 3.1x10^{10} fissions per second would release one watt of power. The complete fission of 1kg of ${}^{235}_{92}U$ spread over a 24 hour period would produce energy in the form of heat at a rate of 1000 MW. If this heat can be turned into electricity with an efficiency of 30%, then the electrical energy would be supplied at the rate of 300 MW. This output is equivalent to that from a large power plant consuming 2500 tonnes of coal per day. It is this equivalence of 1kg of a fissionable material such as ${}^{235}_{92}U$ to 2500 tonnes of coal as a source of electric power that originally made nuclear power attractive, (McMullan J.T. 1977).

Unfortunately, ${}^{235}_{92}U$, the isotope of uranium that readily undergoes fission, is the rarer isotope, being only 0.7% of natural uranium. Most of the rest is ${}^{238}_{92}U$, an isotope for which the possibility of fission is very small, but for which the probability is very high that neutrons slowing down to thermal energies by collisions in the reactor may be absorbed. It would be uneconomic to use pure ${}^{235}_{92}U$ for commercial power production and so it is necessary to find ways of using natural uranium, or slightly enriched uranium, as the fuel in a reaction based on the fission of $^{235}_{92}U$. The answer is to slow down the neutrons as quickly as possible so that there is the least possible chance of the unwanted reactions with $^{235}_{92}U$ taking place. This is done by including a moderator in the core of the reactor.

A moderator is a material in which the fission neutrons can be slowed down to thermal energies (that is to speeds about 2200 ms^{-1}) outside the masses of uranium where the reaction is to go on. In order that a moderator should be efficient, it should absorb the maximum amount of energy from the neutron at each collision. This means that the atoms of the moderator should be as light as possible-ideally they should have the same mass as the neutron. This suggests that water might be a good moderator, which it is, but unfortunately hydrogen is also an extremely good absorber of thermal neutrons, so that water cannot be used as a moderator for natural uranium reactors. Heavy water, in which the hydrogen has already absorbed the neutrons to form deuterium, can be used. Another compromise is to use carbon as the moderator. Carbon is light, common, inexpensive, and easily worked.

The nuclear fission reactor is possible because more neutrons are produced in fission than are needed to initiate it. For example, suppose each fission by a thermal neutron produces n fast neutrons. Some of these will themselves induce fission producing a so called fast fission fraction, ε. In slowing down in the moderator, a fraction p of the $n\varepsilon$ neutrons now available will escape being absorbed by $^{238}_{92}U$, and a fraction f will escape being absorbed in the structural material of the reactor or in the moderator while the neutrons have thermal energies. There will be other losses, for example neutrons may well escape from the core simply because it has a finite size. However, if the core is large enough, these losses can be neglected, and we end up with a very simple expression; that each thermal neutron inducing fission will create k new thermal neutrons where:

$$k=n\varepsilon pf \qquad (4)$$

This is the *four factor formula* and is very important in the design of reactors. Typically for a natural uranium reactor, $n=1.33$, $\varepsilon=1.02$, $p=0.9$ *and* $f=0.9$, so that a typical value for k *is 1.1*. (McMullan J.T. 1977).

When the reactor is running at its desired rate, some way must be found of reducing the factor k *to 1.0*, otherwise the number of fissions will steadily increase, the power generated will increase correspondingly and eventually the core will melt. This is done by using control rods, rods of some material such as cadmium or boron which has a high absorption for thermal neutrons and so can be used to soak up any excess neutrons so adjust k to any desired value.

A possible structure of a nuclear reactor is a large block of moderator into which is inserted the uranium fuel (usually as rods for ease of handling). (See Figure 3). Between the fuel rods would be inserted the control rods, which can be moved in and out according to the value of k needed at any time. This is shown in Figure 2. Very many different types of reactors have been built and are in operation throughout the world. Natural uranium reactors have been built with both heavy water and graphite moderators. Light water moderated reactors have been built using as fuel uranium enriched in $^{235}_{92}U$ to compensate for the extra absorption of neutrons by hydrogen.

The absorption of neutrons by $^{238}_{92}U$, which we have been trying to avoid, can be turned to advantage by using the reaction: (McMullan J.T. 1977).

$$\begin{tikzcd}
{}^{238}_{92}U+{}^{1}_{0}n \arrow[r] & {}^{239}_{92}U \arrow[r] & {}^{239}_{93}Np + {}^{0}_{-1}\beta \arrow[dr] & \\
 & & & {}^{239}_{94}Pu + {}^{0}_{-1}\beta
\end{tikzcd} \qquad (5)$$

to produce an isotope of plutonium, $^{239}_{94}Pu$. This isotope of plutonium has a high probability of undergoing fission when bombarded by slow neutrons and so represents an addition to the fuel content. As a consequence, the loss of neutrons by absorption in $^{238}_{92}U$ is actually a gain as far as overall fuel economy is concerned. In fact, in the process of burning the comparatively rare $^{235}_{92}U$, the natural uranium reactor produces new fuel from the apparently useless $^{238}_{92}U$. This is the basis of the breeder reactor in which more nuclear fuel is produced than is consumed. (McMullan J.T. 1977).

There are two basic types of light water reactor (LWR), the boiling water reactor (BWR), and the pressurized water reactor (PWR). In the BWR, the cooling water boils in the core, and the steam generated is used directly to drive a steam turbine, which drives the generator. The steam is then condensed to water and pumped back to the reactor to complete the cycle. Thus the reactor is the boiler for the whole process. In the PWR on the other hand, the core cooling water is kept at a very high pressure and is heated to some 600 ^{o}C. It is then sent to a separate heat exchanger where a separate water supply is boiled and used to drive the turbine. The problem with the boiling water type is that the cooling water, circulating through the core, becomes radioactive from slight leaks in the thin cladding of the fuel rods and from radioactivity induced by neutrons just outside the cladding. Thus radioactive stream goes directly to the turbine so great care must be exercised to avoid steam leaks in the turbine itself. This difficulty is avoided in the pressurized water system as the cooling water and the steam for driving the turbine are kept separate. Much of the early experience with the pressurized water reactors was gained from nuclear powered submarines, where the nuclear engine, which does not need air for burning, was ideally suited. In addition, cost was no real limitation.

The light water moderated reactor can be criticized:

a) That the welding technology of the heavy steel sheets of the pressure vessels is not capable of providing the necessary reliability. However, the manufacturer's claim that the probability of this happening is quite small and therefore the risk is acceptable.
b) That there is the possibility of sudden failure in the water supply to the core of the reactor, because of a burst or blocked pipe. Emergency water supplies have been designed and installed in all water cooled reactors to combat this type of failure. Luckily (no injuries) and unluckily (no experience gained) this failure has never occurred.

2.1 The Breeder Reactor

All reactors running on either natural or enriched uranium as fuel lose some of their neutrons through absorption by ${}^{238}_{92}U$. In the usual commercial reactors this represents an immediate loss of neutrons though the resulting plutonium does add to the total fuel content of the reactor. This increase in fuel is less beneficial than the loss of neutrons is harmful and so steps are taken to minimize it. In the breeder reactor, however, the capture of the faster neutrons by ${}^{238}_{92}U$ to form ${}^{239}_{94}Pu$ is positively encouraged. No moderator is used in the reactor core to slow the neutrons down rapidly and as a result the capture of neutrons by ${}^{238}_{92}U$, which is most likely at higher speeds, is enhanced. As a consequence the reactor produces significant quantities of plutonium and, in fact, more plutonium fissile material can be produced from the otherwise embarrassing ${}^{238}_{92}U$ than there was ${}^{239}_{94}Pu$ originally-hence the name breeder reactor. It represents the most hopeful chance for a long term power production from nuclear fission.

The breeder reactor has some unpleasant characteristics which are regarded by its critics as rendering it unacceptable for generating electric power. The first of these is that plutonium itself is highly toxic. It also has a very low thermal conductivity which adds to the difficulty of extracting the heat from the reactor core. Further, because there is no moderator, the core runs at a very high energy density and must be cooled, not by water or a gas, but by a liquid metal-sodium. In many designs, the core is surrounded in a blanket of tubes containing non-fissile ${}^{238}_{92}U$ which, by capturing fast neutrons from the reaction in the core, is converted to fissile ${}^{239}_{94}Pu$ (https://en.wikipedia.org/wiki/**Breeder_reactor)**

We have a staggering nuclear waste problem created by a political decision that we could solve simply by reversing that original decision. We also have a perfectly viable way or resurrecting clean and safe nuclear power simply by making the political decision to develop it.

There is no compelling reason to delay shifting our dependence from fossil to nuclear fuel, and redirecting our nuclear focus to Breeder Reactors. We have the ability to control our own energy destiny if we only have the courage to renounce past executive errors and to embrace viable new technologies.

3. The fast breeder reactor

As of 2006, all large-scale FBR power stations have been **liquid metal fast breeder reactors (LMFBR)** cooled by liquid sodium. These have been of one of two designs:

- *Loop* type, in which the primary coolant is circulated through primary heat exchangers outside the reactor tank (but inside the biological shield due to radioactive sodium-24 in the primary coolant)
- *Pool* type, in which the primary heat exchangers and pumps are immersed in the reactor tank

All current fast neutron reactor designs use liquid metal as the primary coolant, to transfer heat from the core to steam used to power the electricity generating turbines. FBRs have been built cooled by liquid metals other than sodium—some early FBRs used mercury, other experimental reactors have used a sodium-potassium alloy called

NaK. Both have the advantage that they are liquids at room temperature, which is convenient for experimental rigs but less important for pilot or full scale power stations. Lead and lead-bismuth alloy can be used. Use of lead or sodium offers merits/demerits. Looking further ahead, three of the proposed generation IV reactor types are FBRs: (https://en.wikipedia.org/wiki/**Breeder_reactor)**

- **Gas-Cooled Fast Reactor** (GFR) cooled by helium.
- **Sodium-Cooled Fast Reactor** (SFR) based on the existing Liquid Metal FBR (LMFBR) and Integral Fast Reactor designs.
- **Lead-Cooled Fast Reactor** (LFR) based on Soviet naval propulsion units.

FBRs usually use a mixed oxide fuel core of up to 20% plutonium dioxide (PuO_2) and at least 80% uranium dioxide (UO_2). Another fuel option is metal alloys, typically a blend of uranium, plutonium, and zirconium (used because it is "transparent" to neutrons). Enriched uranium can also be used on its own.

The plutonium-239 (or the fissile uranium-235) fission cross-section is much smaller in a fast spectrum than in a thermal spectrum, as is the ratio between the $^{239}Pu/^{235}U$ fission cross-section and the ^{238}U absorption cross-section. This increases the concentration of $^{239}Pu/^{235}U$ needed to sustain a chain reaction, as well as the ratio of breeding to fission. (https://en.wikipedia.org/wiki/**Breeder_reactor)**

On the other hand, a fast reactor needs no moderator to slow down the neutrons at all, taking advantage of the fast neutrons producing a greater number of neutrons per fission than slow neutrons. For this reason ordinary liquid water, being a moderator as well as a neutron absorber, is an undesirable primary coolant for fast reactors. Because large amounts of water in the core are required to cool the reactor, the yield of neutrons and therefore breeding of ^{239}Pu are strongly affected. Theoretical work has been done on reduced moderation water reactors, which may have a sufficiently fast spectrum to provide a breeding ratio slightly over 1. This would likely result in an unacceptable power derating and high costs in an liquid-water-cooled reactor, but the supercritical water coolant of the SCWR has sufficient heat capacity to allow adequate cooling with less water, making a fast-spectrum water-cooled reactor a practical possibility. (https://en.wikipedia.org/wiki/**Breeder_reactor)**

4. Radioactive waste

The possible results of an accident in a nuclear power plant are frightening; even worse is the implications for the future posed by the long term storage problems associated with the waste products. (Hinrichs R.A-2006; Sekimoto H-2007; IAEA-1959).

When the neutron strikes the ${}^{235}_{92}U$ or ${}^{239}_{94}Pu$ nucleus, amalgamates with it and causes fission, it does so because the nucleus has too many neutrons compared to its number of protons, and is therefore unstable. The nucleus breaks into two unequal parts together with some fission neutrons. The ratio of neutrons to protons in the stable nuclei increases with the atomic number Z. Thus, both fission fragments have too many neutrons for stability at their atomic number, and are therefore, also radioactive.

$$Xe_{54} \xrightarrow{{}^{0}_{-1}\beta} Cs_{55} \xrightarrow{{}^{0}_{-1}\beta} Ba_{56} \xrightarrow{{}^{0}_{-1}\beta} La_{57} \xrightarrow{{}^{0}_{-1}\beta} Ce_{58} \text{ (stable)} \qquad (6)$$

We have, as a direct result of the fission process, many direct fission fragments, which are radioactive, and in addition, chains of radioactive decays to other radioactive nuclei as part of the search for stability. Unfortunately, some of these radioactive decay products are extremely long lived. For example, Sr^{90}(half life of 28 years) and Cs^{137} (half life 27 years) must be stored for over 500 years to reach the recommended 20 half lives- i.e. one millionth of the original activity. The power we generate today builds up a legacy of problems for our offspring unto the 20th generation. The decision to embark on nuclear energy programmes cannot be taken lightly.

In the past, nuclear waste has been stored in a variety of different ways: in large concrete tanks, either above or under the ground, in disused mines, in porous soil beds, in salt beds deep underground, at the bottom of oceanic trenches .(IAEA-1959)

Salt bed disposal experiments were discontinued after fears became widespread that water might dissolve the salt and allow the radioactive waste to contaminate the ground water supply. Burial in porous soil beds was discontinued after it became apparent that in one particular case in the United States, Trench Z9, the soil bed was found to be acting rather like an enormous chromatograph column and was preferentially segregating out different radioactive waste products at different depths. It was feared that the soils were approaching critical density so that fears of a nuclear incident were rising. The AEC were given authorization to dig it up again and remove the soil to a safer depository. (IAEA-1959)

Other more esoteric methods of disposal are burial in the Antarctic polar ice cap where the container would melt its way through the ice cap under the effect of its own radioactive heating, until it comes to rest on the ground. Other suggestions are to send the waste into the sun in a rocket, or to bury it in the junction of two of the earth's tectonic plates so that it will be dragged down under the earth's mantle for a few million years. In view of the difficulties, however, it is probable that the concrete storage farms will remain a long term feature of radioactive waste disposal. (IAEA-1959)

Disposing of radioactive waste has several different aspects. Firstly there is the conventional problem of storing chemically active material. Secondly there is the problem of radioactive containment, but this causes no great difficulties and really only means thicker walls to the containment vessels so as to attenuate the radioactive intensities outside the tanks to acceptable levels.(Shaw T.L-1984; IAEA-1959)

5. Future Plants

An indigenous FBR under construction in India, was due to be completed in 2012. The FBR program of India includes the concept of using fertile thorium-232 to breed fissile uranium-233. India is also pursuing the thorium thermal breeder reactor. A thermal breeder is not possible with purely uranium/plutonium based technology. Thorium fuel is the strategic direction of the power program of India, owing to their large reserves of thorium, but worldwide known reserves of thorium are also some four times those of uranium. India's Department of Atomic Energy (DAE) says that it will simultaneously construct four more breeder reactors of 500 MWe each including two at Kalpakkam.(https://en.wikipedia.org/wiki/Thorium-based_**nuclear_power**)

China has employed Fast Reactor in recent years, commissioning the 25 MW(e) China Prototype Fast Reactor (CFRP) in July , 2011. China has the challenge of cities polluted by fossil fuel waste products and high energy demands.

France, South Korea, Japan, USA, Germany , Britain etc all have Nuclear Power Energy programmes. Much of the present capacity is LWR and PWR. The USA cut funding for research in FBRs. But opinion seems to suggest that FBRs are an option that can both increase the amount of fissile fuel a hundredfold and reduce the plutonium nuclear waste stockpile. Faced with such realities, Japan has found it wiser to stay with the Nuclear energy option in spite of Fukushima. Japan is warily restarting her nuclear generators.

The traveling wave reactor proposed in a patent by Intellectual Ventures is a fast breeder reactor designed to not need fuel reprocessing during the decades-long lifetime of the reactor. The breed-burn wave in the TWR design does not move from one end of the reactor to the other but gradually from the inside out. Moreover, as the fuel's composition changes through nuclear transmutation, fuel rods are continually reshuffled within the core to optimize the neutron flux and fuel usage at any given point in time. Thus, instead of letting the wave propagate through the fuel, the fuel itself is moved through a largely stationary burn wave. This is contrary to many media reports, which have popularized the concept as a candle-like reactor with a burn region that moves down a stick of fuel. By replacing a static core configuration with an actively managed "standing wave" or "soliton" core, TerraPower's design avoids the problem of cooling a highly variable burn region. Under this scenario, the reconfiguration of fuel rods is accomplished remotely by robotic devices; the containment vessel remains closed during the procedure, and there is no associated downtime.(https://en.wikipedia.org/wiki/Thorium-based_**nuclear_power**)

Nuclear energy programmes face a lot of challenges; radiation, risk of accident, nuclear waste management and risk of nuclear weapons proliferation. Weak third world governments, with poor technology and dysfunctional corrupt structures naturally find the problems even more daunting. If one considers political pressures and fears from interest groups, it begins to become clear why Nuclear energy for many third world governments will likely remain a dream for the foreseeable future.

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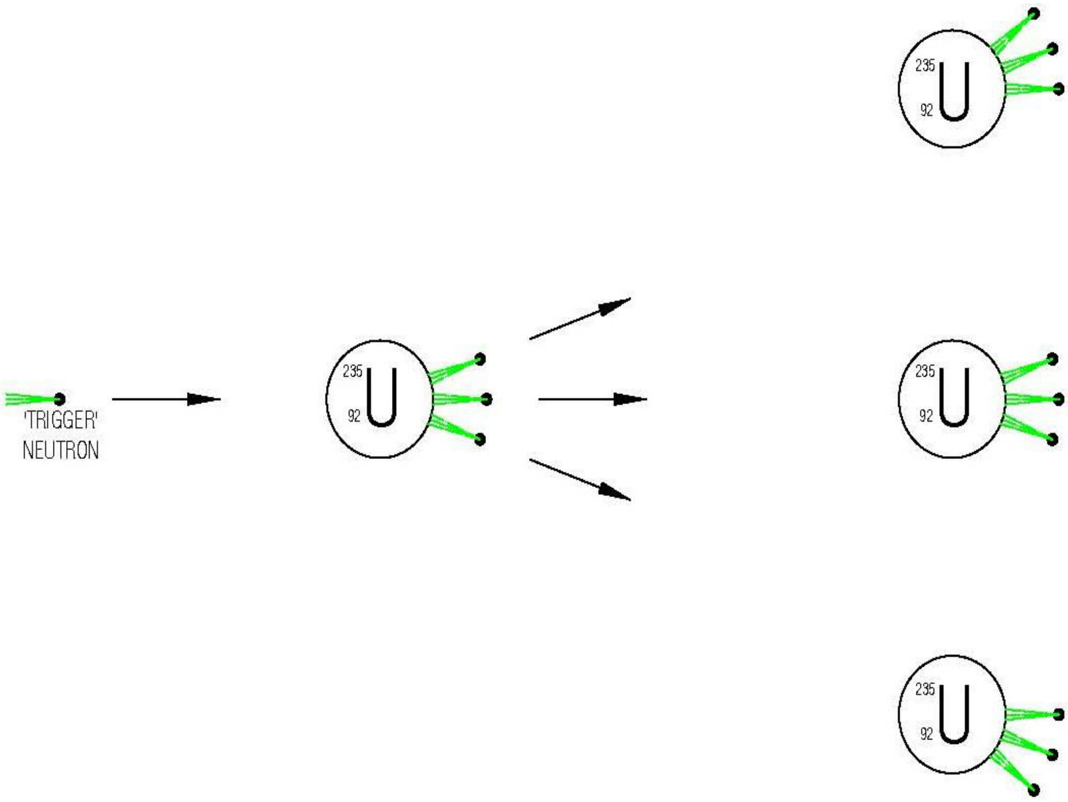

Figure 1. Chain fission of $^{235}_{92}U$ atoms.

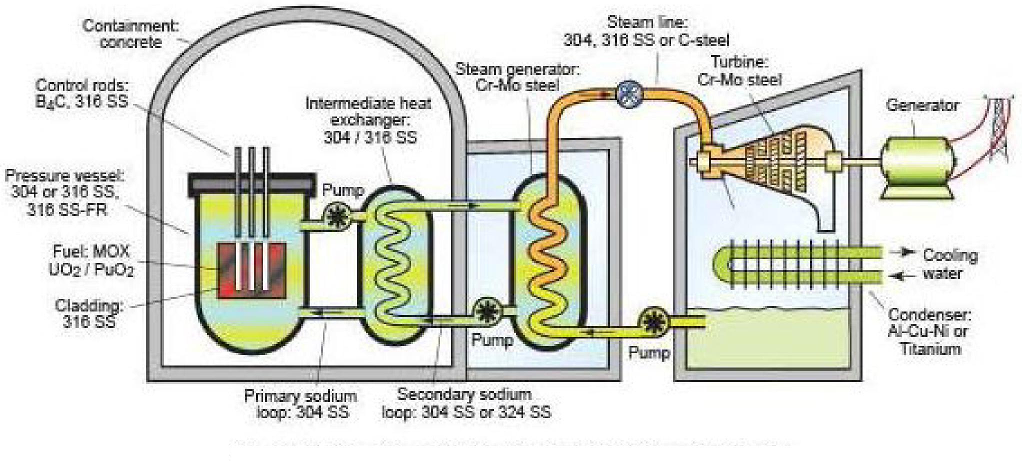

Figure 2. Liquid Metal cooled Fast Breeder Reactor (LMFBR),(Ashby M.F 2010).

Figure 3. Fuel bundle made of zirconium metal tubes, loaded with uranium dioxide. (Oxenhorn,1979).

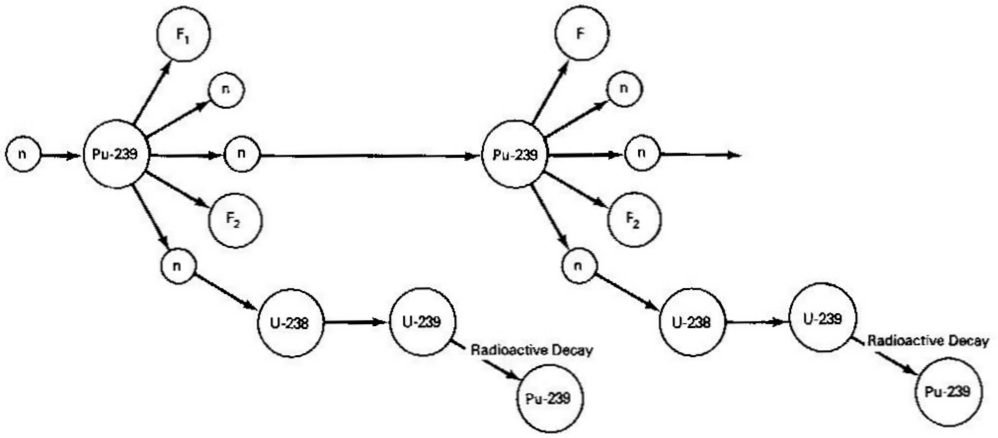

FIGURE 4 Two steps in the chain reaction in a plutonium reactor. Here, a fissionable Pu-239 atom is created for each Pu-239 atom consumed.

(Source:www.personal.utulsa.edu/~kenneth-weston/chapter 10pdf)

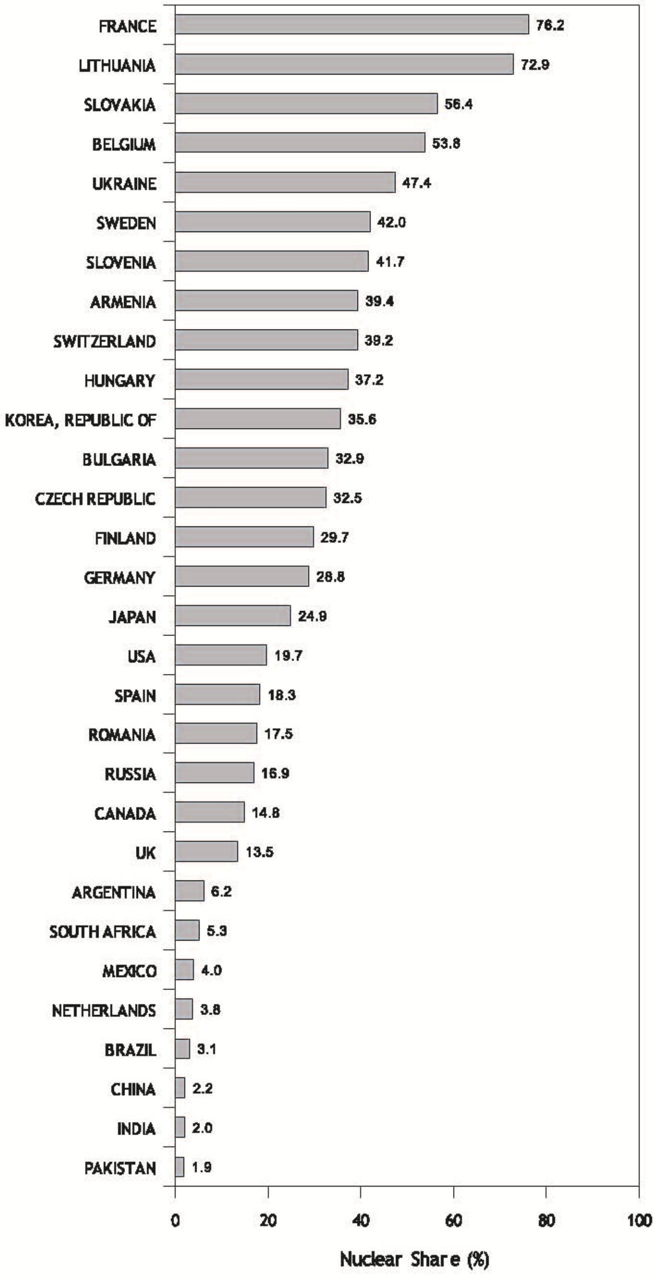

FIGURE 5 NUCLEAR SHARE OF TOTAL ELECTRICITY GENERATION IN 2008 (IAEA 2009)

14

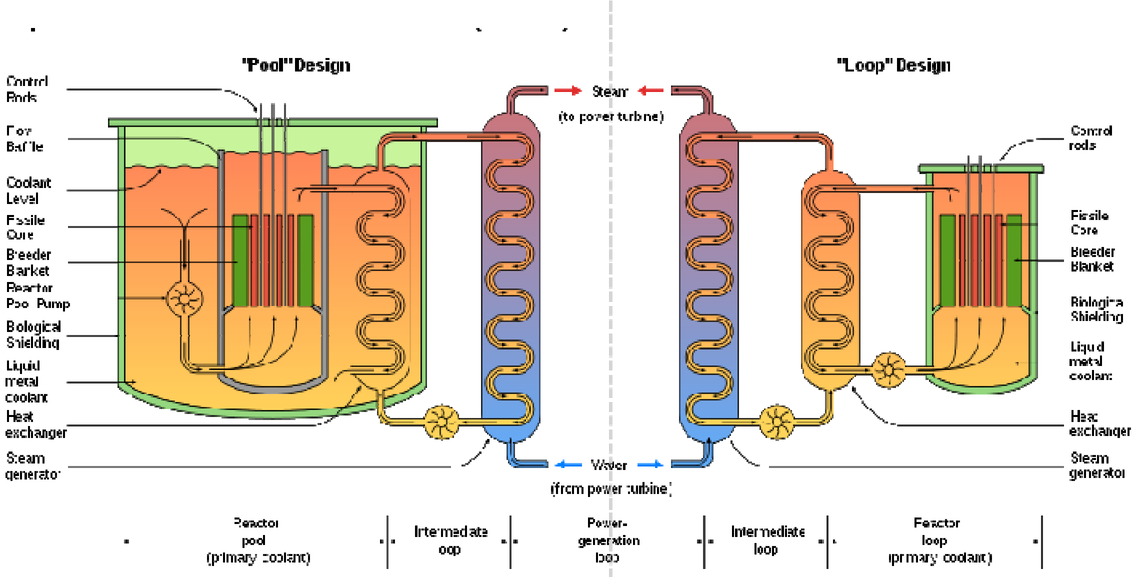

Figure 6: Liquid Metal cooled Fast Breeder Reactors: Pool and Loop Designs (https://en.wikipedia.org/wiki/**Breeder_reactor**)