Section 1

Nuclear Energy and Nuclear Weapons: An Introductory Guide

Nuclear Materials

A chemical element consists of basic building blocks, called atoms, which themselves contain 'sub-atomic' particles. These particles are of three types: protons, neutrons and electrons. Protons (positively charged particles), together with neutrons (uncharged particles) make up an atom's core or nucleus. Electrons (negatively charged particles) are identical in number to the protons, but are found outside of the nucleus of the atom. All chemical elements are defined and distinguished from each other by the number of protons/electrons their atoms contain, termed their atomic number. Examples of atomic numbers are 1 for an atom of hydrogen and 93 for an atom of plutonium.

While all atoms of an element must have the same number of protons/electrons, they may contain differing numbers of neutrons. These variants are called isotopes of an element. They have different nuclear properties and masses/weights but their chemical properties are identical: thus they can only be separated by making use of their differing masses, and not by chemical means.

Isotopes are normally identified by the sum of their protons and neutrons. Thus 'Uranium 235', often shortened to the notation 'U^{235}' (or 'U-235') indicates the isotope of uranium that contains 235 (92+143) protons and neutrons in the nucleus of each atom. 'Plutonium 239', or 'Pu^{239}' (or 'Pu-239') indicates the isotope of plutonium that contains 239 (93+146) protons and neutrons in the nucleus of each atom.

Nuclear Reactions

Fission

Nuclear fission is the splitting of the nucleus of an atom into two or more parts. This is a process which normally only occurs when heavy elements such as uranium and plutonium are bombarded by neutrons under favourable conditions. Not all isotopes of these elements fission under such circumstances; those that do are called fissile materials. The most frequently used fissile materials are the isotopes Uranium 235 (U-235) and Plutonium 239 (Pu-239).

These isotopes are not found in their pure form in nature. U-235 forms only 0.7 per cent of natural uranium ore which is mostly made up of non-fissile U-238. Plutonium does not exist at all in natural form and has to be manufactured from uranium. This is done by placing it inside a reactor, where some U-238 nuclei will capture slow moving neutrons to form fissile Pu-239.

When a fissile material is bombarded with neutrons, it splits into atoms of lighter elements. This process releases large quantities of energy and neutrons. If these neutrons hit and split additional 'fissile' nuclei, more neutrons are released to continue the reaction. If there is a sufficient concentration of atoms of fissile isotopes, known as a 'critical mass', this reaction will be self-sustaining. This is a 'chain reaction'.

A critical mass is the smallest amount of material required for a chain reaction. This may be affected by variables such as the concentration of the fissile isotopes in the material; its density — if it is compressed the critical mass is reduced; and its physical configuration — a sphere or some other shape.

Fusion

Fusion takes place when two nuclei of light elements such as hydrogen fuse together to make a heavier one. While this process releases much larger quantities of energy than the fission process, it also requires large amounts of energy to initiate it. For fusion to occur, the repellant forces that arise between the positively charged protons in the two nuclei have to be overcome, and temperatures of over 100 million degrees centigrade are normally required for this to occur. The most frequently used materials to generate fusion reactions are tritium (H-3), deuterium (H-2) and the solid Lithium-6 Deuteride, which when heated to the temperature of the fusion reaction, breaks down into tritium and deuterium.

Nuclear Reactors

Fission Reactors

There are several features common to all fission or (as they are more usually termed) nuclear reactors.

The first of these is that they contain a core or mass of fissile material (the fuel) which may weigh tens of tons, within which energy is produced by sustaining a regulated chain reaction. The fissile material used varies between reactor types, but it may be natural uranium (which contains 0.7 per cent fissile U-235) or uranium which has been enriched to increase the percentage of U-235 to around 3 per cent. Alternatively, plutonium 239 produced by the irradiation of U-238 in a reactor, or uranium 233 (U-233) produced from thorium 232 (Th-232) may be used, or a combination of these mixed with uranium (mixed oxide fuels or MOX). This fuel is usually in rod or pin form, and is clad in a gastight containment material such as stainless steel.

A second related feature is the presence of a means of regulating the chain reaction. This normally takes the form of control rods which absorb neutrons, and which can be inserted into the core to reduce the rate of fission or to shut down the reactor.

The fissile core of a reactor is usually surrounded by a third common feature, a moderator. This material is chosen because it slows down some of the faster neutrons so that these can more easily hit nuclei and initiate fission, and thus maintain the chain reaction. The moderator can be ordinary (or light) water, heavy water (deuterium oxide) or graphite.

A fourth common feature is a means of removing the heat produced by the chain reaction from the core of the reactor. This cooling system can also provide the heat and steam to drive turbines and thus generate electricity.

Finally, there is a containment vessel which serves to shield the radioactive core from other parts of the reactor system. Lining this vessel is a reflector which increases the efficiency of the fission process. In addition, a reactor will itself normally be surrounded by a further thick containment structure, whose purpose is to contain any release of radioactivity and prevent it escaping into the surrounding environment.

Reactors have been built to serve four broad purposes. First, a significant proportion of the reactors in the world are large units designed to produce steam to drive turbo-generators, and thus to generate electricity for civil uses. Second, there are smaller units of a similar type which are used in naval vessels, especially submarines, to generate electricity for propulsion purposes or to drive turbines. Third, there are many small materials testing and research reactors, which usually have no turbo-generators attached and are used mainly for experimental purposes. For many years these used small kilogram quantities of highly enriched uranium as fuel, but its proliferation potential has led to a global attempt to replace it with fuel of lower enrichment. Finally, there are large units used by the nuclear-weapon states to produce plutonium for military explosive purposes, some of which do not have turbo-generators attached to them.

There exist five different nuclear reactor technologies:

Light Water Reactors (LWRs)

This is the most widespread power reactor type found in the world today. It uses low enriched (3%) uranium as fuel, which enhances its efficiency as an electricity generator by enabling the fuel to stay longer in the reactor. It also uses ordinary water as both a moderator and coolant. There are two variants of this reactor, Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs), the chief difference between them being in their method of producing steam to make electricity. Small LWRs are also used to power submarines and other naval vessels. LWRs are a costly and inefficient way of producing Pu-239.

Heavy Water Reactors (HWRs)

In these type of reactors, heavy water is used as both the moderator and coolant. Heavy water absorbs so few neutrons that it permits the use of natural uranium as fuel. This type of reactor, the majority of which are called CANDUs, uses up so much of the fissile U-235 in its natural uranium fuel that it is probably uneconomic to reprocess and recycle it, and the preferred option is to store it and dispose of it as waste. It is also a good producer of plutonium, and this type of reactor has been used in the United States without any turbo-generators attached to produce materials for weapon purposes. To produce Pu-239, rather than to minimize electricity generation costs, fuel re-loading takes place more frequently. Thus a distinction between civil and military use is the length of time the fuel remains in the reactor.

Gas Cooled Reactors (GCRs or MAGNOX)

These are moderated with graphite and cooled with carbon dioxide gas. Most use natural uranium fuel encased in a magnesium oxide-based cladding called MAGNOX. As this corrodes if stored in water, it needs to be reprocessed for environmental and safety reasons. Its design originated in the reactors used to produce plutonium for military purposes in France, the United Kingdom and the USSR.

High Temperature Gas Cooled Reactors (HTGRs)

The HTGR is cooled with helium gas and moderated with graphite. Highly enriched uranium is used as fuel (93 per cent U-235), though this may be mixed with Th-232. The attraction of this type of reactor is that much of the uranium in the fuel is burned up, requiring infrequent reloading, and the extremely high operating temperatures enable it to be linked to very efficient, modern turbo-generators when used to produce electricity.

Liquid Metal Fast Breeder Reactors (LMFBRs)

Breeder reactors normally have a core of highly enriched uranium or plutonium, which can produce enough surplus neutrons to convert U-238 in a blanket around the core into Pu-239 at a rate faster than its own consumption of fissile material. They thus produce more fuel than they consume. They operate without a moderator, and at very high temperatures. The coolant is normally a liquid metal, such as sodium, which allows for the rapid removal of heat. These reactors have traditionally been seen as a means of utilising the plutonium produced by the other types of reactor, but are also capable of producing plutonium ideal for use in weapons.

Fusion Reactors

Although many attempts have been made to produce a working fusion reactor, these only exist in experimental form. The temperatures at which fusion is achieved are so great that no known material will hold the fusing materials. Containment of the material is being attempted using magnetic fields.

Nuclear Weapons

Fission Devices

A fission weapon or device is designed so that a critical mass of fissile material can be assembled and held together before the device blows itself apart. The yield of the weapon is determined by the amount of fissile material involved, the number of nuclei fissioned, and the number of generations of fissions that can be achieved before disassembly takes place.

A simple fission weapon design, also known as a first-generation nuclear weapon, can be of either the 'gun barrel' or 'implosion type. A gun device involves bringing together rapidly two sub-critical masses of highly enriched uranium by propelling one of them with an explosive along a thick tube or gun-barrel so that it impacts with considerable velocity upon the other. This creates conditions for a chain reaction. This method is conceptually simple but the explosive power of the weapon tends to quickly force the fissile material apart so that little of the material goes through the fission process. It is therefore relatively inefficient in its use of fissile material. This method cannot be used with plutonium.

An implosion weapon works by compressing a sub-critical spherical mass of fissile material until it becomes critical. The fissile material is surrounded by a neutron reflector, usually of beryllium, and a heavy metal tamper of either U-238 or tungsten. Surrounding this assembly is a further hollow sphere of conventional explosives. If the conventional explosive can be detonated so as to produce a uniform, symmetrical implosion, the tamper is propelled inwards into the sphere of fissile material, and compresses it into criticality. The forces generated by the conventional explosives then contain the gaseous sphere of fissile materials while many repetitions of the fissile reaction occur, and the full yield of the device is produced.

Boosted-Fission Devices

A fission device can be 'boosted' to increase its yield by placing within its core a small quantity of fusion material, such as tritium. At the great temperatures and pressures found within the gaseous core of an exploding device, this material fuses and releases an extra quantity of neutrons which, in turn, produce additional fissions in the uranium or plutonium used in the device. More of the fissile material is thus consumed than in a simple fission device, the efficiency of the fission process is improved and a higher yield produced.

Fusion (Thermonuclear) Devices

The energy released by such a device, also known as a second-generation nuclear weapon, arises primarily from nuclear fusion in isotopes of hydrogen such as tritium and deuterium. A large energy source, such as a fission device, is needed to start a fusion reaction. A fusion weapon thus has at least two stages which contribute to the yield, the fission trigger or primary device and the thermonuclear secondary device. In addition, these two devices may be contained in a shell of U-238 which constitutes a third stage of the device. This material, whilst it cannot maintain a self-sustaining fission explosion, can be made to fission where there is a constant external supply of fast neutrons from other fission or fusion reactions. There can be any number of fission-fusion-fission-fusion steps, and so no limit in theory to the size and yield of a thermonuclear weapon.

Nuclear Testing

In order to develop and build an operational nuclear explosive device different types of testing are needed. It is possible to test the functioning of a nuclear weapon with a high degree of reliability not only in a full-scale nuclear explosion, but also through sophisticated tests conducted on a smaller scale. The implosion mechanism of a nuclear weapon can be studied with the help of hydrodynamic experiments (HDEs) where the fissile material in the core is replaced by non-fissile substances. The first stages of an explosive nuclear chain reaction may be observed in hydronuclear experiments (HNEs) where only a small amount of fissile material is placed in the core of a device, allowing it to sustain a nuclear chain reaction for a few generations only. Additionally, subcritical experiments and other laboratory experiments (e.g., nuclear fusion induced by laser ignition) can be used to get a better understanding of the physical processes involved in the development, design and construction of a nuclear explosive device.

Weapon-Grade Fissile Materials

The size of a fission device is directly related to the concentration of fissile isotopes in the material in the core. For purposes of producing a practical weapon, the minimum enrichment required for uranium is about 50 per cent. However, to enable compact, light designs to be produced, the present nuclear powers are assumed to use in their weapons about 10–25 kilos of uranium enriched to over 90 per cent U-235. This enriched material is produced in an enrichment plant (see below).

Plutonium is often preferred to uranium in weapon designs, as less plutonium than uranium is required to produce a given yield — about 5–8 kilos is assumed to be required for a simple device. Plutonium with 93 per cent or above Pu-239 constitutes weapons grade material, though there are claims that devices have been exploded using plutonium with much lower concentrations of this isotope. Such weapons, however, tend to have uncertain yields and give off dangerous radiation, so the higher concentrations are preferred.

All fission reactors produce plutonium, but reasonably pure Pu-239 can only be obtained by withdrawing the uranium fuel after a short period (2–6 months) in the core. If the fuel is left in for a longer period, significant amounts of Pu-240 and other heavier isotopes are contained in the plutonium. Typically, Light Water Rectors (LWRs) will have plutonium in their used fuel which has a concentration of Pu-239 below 80 per cent. Plutonium is obtained from spent reactor fuel through a chemical process known as reprocessing.

Enrichment

Uranium must be enriched if it is to be used in certain reactor types and in weapons. This means that the concentration of fissile U-235 must be increased by physical, rather than chemical, means before it can be fabricated into fuel. The natural concentration of this isotope is 0.7 per cent, but a concentration of 3 per cent is necessary in order to sustain a chain reaction in an LWR. Some 90 per cent enrichment is required before use in HTGRs, the majority of submarine propulsion units or fission weapons. This process of enrichment is not linear, and as much enrichment effort, or 'separative work' as it is usually termed, may be involved in achieving enrichment from, say 0.7 to 1 per cent as from 10–90 per cent.

There are six main techniques for increasing the concentration of U-235:

Gaseous Diffusion

This was the first method of enrichment to be commercially developed. The process relies on a difference in the mobility of different isotopes of uranium when they are converted into gaseous form. In each gas diffusion stage uranium hexafluoride gas (UF6) is pumped under pressure through a porous nickel tube (a cascade) which causes the lighter gas molecules containing U-235 to pass through the porous walls of the tube more rapidly than those containing U-238. This pumping process consumes large amounts of energy. The gas which has passed through the tube is then pumped to the next stage, while the gas remaining in the tube is returned to lower stages for recycling. In each stage, the concentration of U-235 is increased only slightly, and enrichment to reactor grade requires a facility of approximately 1200 stages. Enrichment to weapons grade requires about 4000 stages. Industrial scale facilities of this type require electricity supplies of hundreds of megawatts of power.

Gas Centrifuge

In this type of process uranium hexafluoride gas is forced through a series of rapidly spinning cylinders, or centrifuges. The heavier U-238 isotopes tend to move to the side of the cylinder at a faster rate than the lighter molecules containing U-235. The gas at the centre is removed and transferred to another centrifuge, where the process is repeated. As it moves through a succession of centrifuges, the gas becomes progressively richer in the U-235 isotope. Electricity requirements for this process are relatively low compared with gaseous diffusion, and as a consequence this process has been adopted for most new enrichment plants.

Aerodynamic Separation/Becker Process

The Becker technique involves forcing a mixture of hexafluoride gas and either hydrogen or helium through a nozzle at high velocity and then over a surface in the shape of a curve. This creates centrifugal forces which act to separate the U-235 isotopes from the U-238. Aerodynamic separation necessitates fewer stages to achieve comparative enrichment levels than either gaseous diffusion or gas centrifuges but consumes much more energy.

Laser Enrichment

The laser enrichment technique involves a three stage process; excitation, ionization and separation. There are two techniques to achieve these effects, the 'Atomic' approach, and the 'Molecular' approach. The Atomic approach is to vaporize uranium metal and subject it to a laser beam at a wavelength that excites only U-235 molecules. The vapour is then exposed to a second laser beam that ionizes the U-235 atoms, but not the unexcited U-238 atoms. Finally, an electric field sweeps the U-235 atoms onto a collecting plate. The Molecular approach also relies on differences in the light absorption frequencies of uranium isotopes, and begins by exposing molecules of uranium hexafluoride gas to infra red laser light. U-235 atoms absorb this light, thereby causing an increase in their energy state. An ultra-violet laser can then be used to break up these molecules and separate the U-235. This process has the potential to produce very pure U-235 with minimum energy requirements, but has not yet advanced to an industrial scale level of production.

Electro-Magnetic Isotope Separation (EMIS)

The EMIS process of enrichment is based on the fact that an electrically charged atom, travelling through a magnetic field, moves in a circle whose radius is effected by the ion's mass. EMIS is achieved by creating a high current beam of low energy ions and allowing them to pass through a magnetic field created by giant electro- magnets. The lighter isotopes are separated from heavier isotopes by their differing circular movements.

Chemical Separation

'Chemical Separation' is something of a misnomer as the differing isotopes of an atom are chemically identical. This form of enrichment exploits the fact that ions of these isotopes will travel across chemical 'barriers' at different rates because of their different masses. There are two methods to achieve this: the method developed in France of solvent extraction; and the process of ion exchange used in Japan. The French process involves bringing together two immiscible liquids in a column, giving an effect similar to that of shaking a bottle of oil and water. The Japanese ion exchange process requires an aqueous liquid and a finely powdered resin which slowly filters the liquid.

Reprocessing

This is a process whereby the uranium and the plutonium in spent fuel discharged from a reactor is separated from the other 'fission products' by chemical means. It may then be recycled into reactor fuel or, in the case of plutonium, may be used in weapons. Reprocessing is usually carried out using mechanical and solvent extraction techniques, and occurs in three steps.

Solution

After a period of storage to reduce their radioactivity the fuel assemblies are cut into short sections in what is termed the 'head-end' stage. These pieces are then placed in a nitric acid solution to dissolve the fuel. This acid solution is centrifuged to remove undissolved solids, and chemically treated in preparation for the separation process.

Separation

In this separation stage the ‘Plutonium Uranium Recovery by Extraction’ (PUREX) method may be employed, with the solution being fed into extraction columns and mixed with various chemicals. The plutonium and uranium emerge from this in the form of nitrates.

Purification

The third stage involves purifying the recovered materials. Recovered uranium can be recycled into new fuel, although sometimes this involves further enrichment. Recovered plutonium may be used as fuel in breeder reactors, to make mixed oxide (MOX) fuel or, if of a suitable isotopic composition, to make weapons.