NEQ READING MATERIAL ON NUCLEAR

INTRODUCTION

The economic development of any nation largely depends on how its energy requirements are satisfied. Fuel and power are crucial for scientific and technological progress. As a matter of fact, per capita fuel and energy consumption (in particular that of electric power) is one of the basic indicators of this progress. Society's well-being itself hinges on power engineering and energy consumption. For the majority of the world's population the quality of human life is directly related to the level of per capita energy availability. Capacity development and knowledge management in the energy sector is therefore pivotal to ensuring sustainable progress.

This document is a compilation of literature on topical issues approved by the organizers of the National Energy Quiz (NEQ) competition and included in the curriculum developed by the Localization and Stakeholder Support Centre of the Nuclear Power Institute, Ghana Atomic Energy Commission for use in the conduct of the National Energy Quiz (NEQ) competition among second cycle as well as technical schools in Ghana.

The document is to provide a compact source of information for second cycle students in general and participants of NEQ competitions specifically on nuclear. It is also intended to enhance students' interest and foster a paradigm shift in the study and understanding of specific nuclear related issues.

Chapter 1 of this document discusses, nuclear industry, origin and future, chapter 2 presents nuclear fuel cycle and technology. In chapter 3, the document looks at developing a country's nuclear power programme whiles chapter 4 present specifics on developing Ghana's nuclear power programme and finally in chapter 5, legal and regulatory framework in developing nuclear power programme is discussed.

Students and teachers are encourage to thoroughly abreast themselves with these foundation module of the nuclear energy sector by assimilating all concepts herein and do so in addition to getting information from all other referenced documents that are cited. Table 1 shows the NEQ curriculum on nuclear

Table 1: The NEQ Curriculum on Nuclear

Nuclear Industry: Origin & Future	**Nuclear Fuel Cycle and Technology**	**Developing a Country's Nuclear Power Programme**	**Ghana's Nuclear Power Programme**	**Legal and Regulatory Framework**
International Context of the Nuclear Industry and its development	Nuclear Fuel Cycle	Why Nuclear	Ghana's Nuclear Journey	International Legislative Regime
Successful Nuclear Reactor Designs and Types of Nuclear Reactors	Basic Nuclear Physics	Key Organisations in the Development of a country's nuclear programme and their roles	Ghana's Generation Mix and Challenges	Nuclear Industry Regulatory Regime
Accidents in the Nuclear Industry	Nuclear Power Generation	Milestones in the Development of a Country's Nuclear Power Programme	Status of Ghana's Nuclear Power Programme	Emergency Preparedness and Incident Management
Impact of Nuclear Accidents	Nuclear Waste Management & Disposal	Nuclear Power Programme Infrastructural Issues and their Relevance	Role and Function of Ghana Atomic Energy Commission and the Nuclear Power Institute	Fundamentals of Nuclear Security, Safety & Safeguards
Nuclear Renaissance	Application of Nuclear Materials and Technology	Stakeholders in Nuclear Power Programme Development and their roles and responsibilities	Role and Function of the Nuclear Power Ghana	Technical Support & Local Industry Development for Sustainable Nuclear Power Programme
The Future of Nuclear Power	Nuclear Reactor Components and Defense In-depth	The International Atomic Energy Agency	Role and Function of the Nuclear Regulatory Authority	Advance Nuclear Reactor Concepts

CHAPTER 1: Nuclear Industry, Origin and Future

This chapter is intended to help understand the international context of the nuclear industry and the key factors that affect its development.

1.1. International Concept of the Nuclear Industry and its Development

The origins of the civil nuclear industry began in the nuclear weapons programmes developed in the 1940s. Since then, civil nuclear power has expanded rapidly, most notably in the 1970s. Nuclear power has one of the smallest carbon footprints of any major energy source and is currently used in over 30 countries to produce approximately 12% of global electricity.

A number of accidents and incidents have influenced some countries to reconsider the use of nuclear energy, whilst other countries are rapidly expanding their capacity. Forecasts indicate that global nuclear energy production will double by 2040.

Post-war economic growth required abundant and reliable sources of energy. As a result, the United States, Canada, United Kingdom, France and the Soviet Union started applying the knowledge they gained about atomic energy during the 1940s to the peaceful use of nuclear power generation. In 1953 U.S. President Dwight Eisenhower addressed the United Nations in a speech that has come to be known as "Atoms for Peace." In the speech, Eisenhower called for international co-operation in the development of nuclear technology for peaceful purposes.

The world's first nuclear power station to supply electricity for domestic use was developed in the Soviet Union. It is the RBMK reactor (the Beloyarsk NPP) that was connected to the Soviet power grid at Obninsk in 1954. This power plant used a water-cooled reactor fuelled by natural uranium and had a graphite core. After almost 48 years of operation, it was shut down in 2002. In 1956 the Soviet Union developed the world's first fast reactor and also a nuclear-powered icebreaker (the Vladimir Lenin) in the late 1950s.

In 1954, the UK Atomic Energy Authority (UKAEA) was set up to oversee the development of civil nuclear technology in the United Kingdom. Two years later, a power station at Calder Hall, Cumbria, was connected to the national grid. The two reactors at Calder Hall were a prototype of the Magnox gas-cooled reactor, whose design was eventually used for 11 power stations in the UK, as well as at one power station in Japan and one in Italy.

Magnox reactors have a graphite moderator and use pressurised CO_2 as the coolant. In 1964 the Advanced Gas-Cooled Reactor (AGR) superseded the Magnox design in the UK. In the AGR, the material used for the fuel cladding was changed from Magnox to stainless steel, which allowed for higher temperatures and greater thermal efficiency. Seven power stations, each using two AGR reactors, were eventually built in the UK.

France adopted an independent approach in both military and nuclear power-generation outside NATO. Its gas-graphite reactor, the UNGC, was similar in design to the UK's Magnox, but the fuel cladding was made from a magnesium-zirconium alloy. The first reactor of this type—the G-2 (Marcoule)—went online in 1959. Nine units based on this design were eventually built.

With an abundant supply of uranium, Canada also developed nuclear technology. The Canadian nuclear industry chose to use "heavy water," which is a combination of deuterium and oxygen (D2O), as a moderator. Several reactors were eventually built using heavy water, notably the NRX reactor at Chalk River, Ontario. In 1952 the Atomic Energy of Canada Limited (AECL) was set up to take over the Chalk River complex and develop the peaceful applications of nuclear energy. Between 1954 and 1973 the AECL built four heavy water reactors, for which the name CANDU (CANada Deuterium Uranium) was used. Among CANDU's features are a more efficient use of uranium (the use of natural rather than enriched uranium as a fuel is possible because of heavy water) and the successful implementation of on-power refuelling. AECL has supplied reactors to Canada and exported them to several parts of the world, notably India, China, South Korea and Pakistan.

1.1.1 Some Factors that Shaped the Nuclear Industry

In 1973, an oil embargo was imposed and followed subsequent by the quadrupling of oil prices. These occurrences spurred the United States, Europe and Japan to search for alternatives to petroleum. Petroleum as a source of power generation was consequently phased out in favour of an increased reliance on nuclear power. Between 1973 and the early 1990s, nuclear energy's share of U.S. electricity increased from 4% to 20%, while the share from oil dropped from 17% to 4%.

The growth of nuclear power in the 1970s was most dramatic in France, where Energy De France (EDF) embarked on an intensive programme of nuclear plant construction using Framatome's N4, the first 100% French design of a Pressurized Water Reactor (PWR). The first of 34, 900MW reactor units started up operations at Fessenheim in 1977. Nuclear contribution to electricity production in France rose from 8% in 1974 to 75% today. France currently exports electricity to England and Italy and has exported its PWR technology to Belgium, South Africa, South Korea and China.

Where France led, other European countries followed. In West Germany, 17 reactors came online between 1975 and 1989. All were constructed by Siemens-KWU and provided one-third of the electricity of united Germany. By the end of the 1970s, Italy, Spain, the Netherlands and Switzerland had built reactors, as had Czechoslovakia, Bulgaria, Japan, Argentina and North Korea.

Beginning in the 1970s, a number of factors began to affect the growth of nuclear power. One of the most important involved finances. The turnkey contracts of the late sixties and early seventies lost money for their manufacturers, dashing the hope that nuclear power would be "too cheap to meter" (Lewis Strauss, Chairman, U.S. Atomic Energy Commission, 1954).

A second factor was the discovery of huge quantities of natural gas in the North Sea from the 1950s to the 1970s; this provided large parts of Europe with a cheap and attractive alternative to nuclear power.

A third factor involved a number of safety accidents at nuclear plants, which caused mounting concern about possible damage to human health and the environment.

A fourth factor occurred in 1974 when India detonated a nuclear bomb in an underground nuclear test, leading to fears of nuclear proliferation.

A fifth factor is the birth of the environmental movement that took place in the 1970s and that has mostly opposed nuclear power. For example, in 1970, the United States created the Environmental Protection Agency; the tougher environmental regulations that it put into place made nuclear plants more expensive to build.

1.2. Successful Nuclear Reactor Designs and Types of Reactors

Over the years, only two major reactor designs achieved commercial success: the Light Water Reactors (LWRs), which include both the Boiling Water Reactor and the Pressurised Water Reactor, and the CANDU which uses Heavy Water. The PWR's commercial success has been confirmed by decisions made in France and the UK. In France under President Charles De Gaulle, the adoption of a U.S. reactor design in France was unthinkable. In 1969, however, De Gaulle's successor, Georges Pompidou, reversed this policy by authorising EDF, the national utility company, to buy PWRs from Westinghouse. Subsequent reactors in France have all been PWRs.

In the UK, the AGR proved less successful commercially than originally hoped, so in 1978 the UK Government decided to build no more AGRs. Instead, it ordered its first PWR, Sizewell B, from Westinghouse for construction in Suffolk. After a long public enquiry, construction started in 1987 and finished in 1994.

Since then, no additional reactors have been built in the UK. However, a new build programme has been authorised recently by the British Government and plans are now established for a number of new reactors, all of which will be LWRs.

1.1.1 Nuclear Reactor History

The age of nuclear reactors began on December 2, 1942, when witnesses to the first controlled chain reaction heard the rapid clicking noise of a Geiger counter. The sound of the Geiger counter was caused by the splitting of uranium atoms within an array o graphite bricks, uranium metal, and uranium oxide known as the Chicago Pile One (CP-1). Enrico Fermi and 54 others on his team, watched over the experiment, which was held in secret under the grandstands of an old University of Chicago football field. Although Fermi's work led to the development of the atomic bomb, its peaceful uses soon followed. In 195, scientists in Arco, Idaho) generated enough electricity in an experimental reactor to illuminate four light bulbs.

In 1954, President Eisenhower started ground-breaking on America's first commercial nuclear power plant in Shippingport, Pennsylvania. By 1957, the Shippingport Atomic Power Station began supplying electricity to customers of Duquesne Light Company. From the late 1950s through the early 1960s, new nuclear plants of various technologies were designed and ten small demonstration units were built. By 1963, Jersey Central Power and Light Company made an economic case for building a 630 MW nuclear power plant for commercial purposes based on costs competitiveness with fossil fueled power plants. More nuclear power plants followed shortly thereafter, and by 1967 which marked the 25th anniversary celebration of Fermi's experiment, 13 nuclear units were operating in the US. In 1973, 40 nuclear plants were generating four percent of he US electricity.

1.1.2 Reactor Types and Uses

Nuclear Reactors are used for various purposes, but the major use of nuclear reactors in today's world is for the generation of commercial electrical power. The classification of reactors by their functional use is as shown in Table 2.

Table 2: Reactor Types

REACTOR TYPE	FUNCTIONAL APPLICATION
Research	Neutron and gamma irradiation of various materials and samples to study effects of irradiation
Test	To subject newly designed reactor components (particularly fuel assemblies or fuel elements) to the neutron flux, pressure and temperature for which they were designed, so as to evaluate their behaviour and integrity under simulated operating conditions.
Production	To produce special nuclear materials form fertile (source) materials. For example, the production of Plutonium-239 (Pu-239), Uranium- 235 (U-235), or the production of U-233 from Thorium-232 (Th-232)
Naval	For the propulsion of submarines, aircraft carriers and other naval ships
Breeder	To expand and conserve the supply of fissile material. Any reactor that generates more fissile material than it consumes is classified as a "breeder reactor".
Power	To generate electric power by heating water through the use of heat produces from atomic fission reaction to produce steam that drives turbines that in turn drive electrical generators.

A Fertile Material contains fertile nuclide which when irradiated within a reactor produces fissile material. A Fissile Material contains a long half-life nuclide which has a high probability of splitting when there is an interaction with a neutron and is also capable of sustaining nuclear chain reaction.

Reactors are also often described by the type of moderator, coolant or energy magnitude of fission neutron. Classifications based on these descriptions are, heavy water reactor, light water reactor, graphite moderated reactor, gas cooled reactor, light water cooled reactor among others.

Research reactors are usually pool type reactors in that, the reactor core is merely submerged within an open top pool. Such reactors usually have very low power rating of no more than a few kilowatts and some operate at less than 100 watts of thermal energy and hence are sometimes referred to as Zero Power Reactors. The larger commercial power reactors, on the other hand are typically rated at 3300 megawatts thermal (reactor core output in MWt) and 1100 megawatts electrical (generator output in MWe). Breeder reactors are primarily intended to be power reactors but they can also be production reactors or dual purpose production power reactors.

Worldwide, there are 13 basic designs of commercial nuclear power plants, as defined in Table 3. Today there are about 440 nuclear power reactors operating in 30 countries plus Taiwan, with a combined capacity of about 400 GWe. In 2018 these provided 2563 TWh, over 10% of the world's electricity. About 55 power reactors are currently being constructed in 15 countries notably China, India, Russia and the United Arab Emirates.

Table 3: Types of Commercial Nuclear Power Plants

ABBREVIATION	REACTOR TYPE
ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas Cooled Reactor
BWR	Boiling Water Reactor
GCHWR	Gas Cooled Heavy Water Reactor
GCR	Gas Cooled Reactor
HTGR	High Temperature Gas Cooled Reactor
HWLWR	Heavy Water Light Water Reactor
LGR	Light Water Gas Cooled Reactor, Graphite Moderated Reactor
LMFBR	Liquid Metal Fast Breeder Reactor
LMGMR	Liquid Metal Cooled Graphite Moderated Reactor
PHWR	Pressurized Heavy Water Reactor
PLWBR	Pressurized Light Water Breeder Reactor
PWR	Pressurized Water Reactors

Over 100 power reactors with a total gross capacity of about 120,000 MWe are on order or planned, and over 300 more are proposed. Most reactors currently planned are in the Asian region, with fast-growing economies and rapidly-rising electricity demand. Many countries with existing nuclear power programmes either have plans to, or are building, new power reactors.

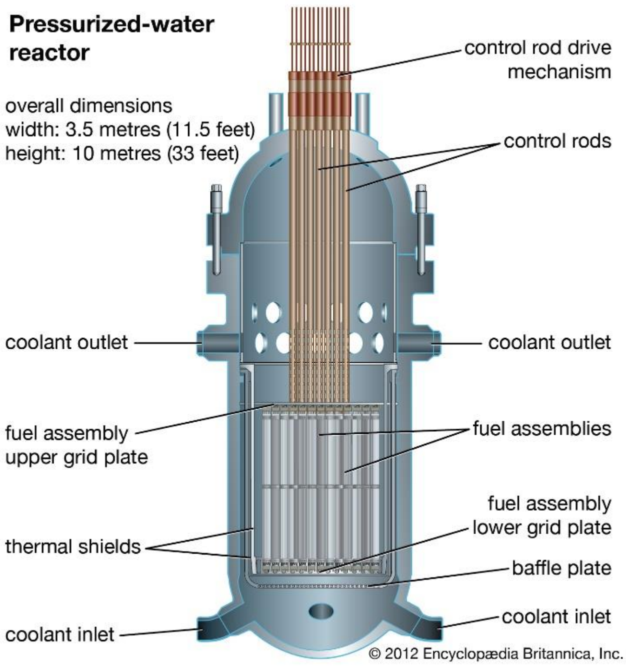


Figure 1: Pressured Water Reactor showing inlets and outlets for water coolant passing through the core

PRESSURIZED WATER REACTORS

The Pressurized Water Reactor (PWR) was originally designed by Westinghouse Bettis Atomic Power Laboratory for military ship applications. Subsequently, the design was modified for commercial applications by the Westinghouse Nuclear Power Division. The first PWR plan in the US was he Shippingport plant, located near Pittsburgh, Pennsylvania.

In addition to Westinghouse, Asea Brown Boveri-Combustion Engineering (ABB-CE), Framatome, Kraftwerk Union, Siemens and Mitsubishi have built PWR type reactors throughout the world. Babcock and Wilcox (B&W) has also built a few PWR but used vertical once-through steam generators, rather than the U-tube design used by the rest of the suppliers

PWRs have three separate water cooling systems for transferring heat. They are, (1) the reactor coolant system also called the primary coolant, (2) the steam generator-condenser system and (3) the condenser cooling system. In the absence of any defects such as cracks or ruptures in the heat exchanger tube of the PWR, only the reactor coolant system will contain any radioactivity. The reactor coolant system may consist of two, three or four cooling loops that provide water to the reactor vessel.

Water in the reactor gets heated as it moves past the fuel assemblies with temperature rising from typically 530 ^{0}F at the inlet to 590 ^{0}F at the vessel outlet. Boiling other than movement of minor bubbles (nuclear boiling) in the water as it heats up is not allowed to occur. Pressure is maintained by a pressurizer connected to the reactor coolant system. Pressure is maintained at approximately 2230 psi through a heater and spray system in the pressurizer. The reactor coolant water is pumped to the steam generator and passes through tubes.

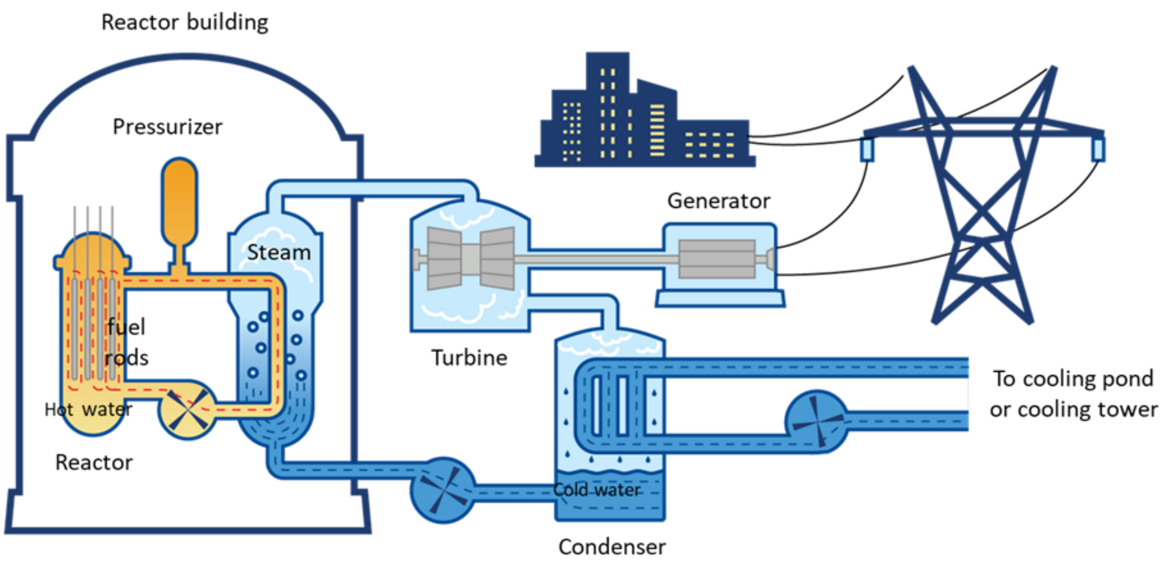


Figure 2: Pressured Water Reactor (PWR) System

In the steam generator-condenser system, cooler water is pumped from the feedwater system and passes on the outside of the steam generator tubes which causes it to be heated and converted to steam. The steam then passes through a main steam line to the turbine, which is connected to an turns the generator. The steam from the turbine condenses in a condenser. The condensed water is then pumped by condensate pumps through the low pressure feedwater heaters, then to the feedwater pumps, then to the high pressure feedwater heaters and then back to the steam generators.

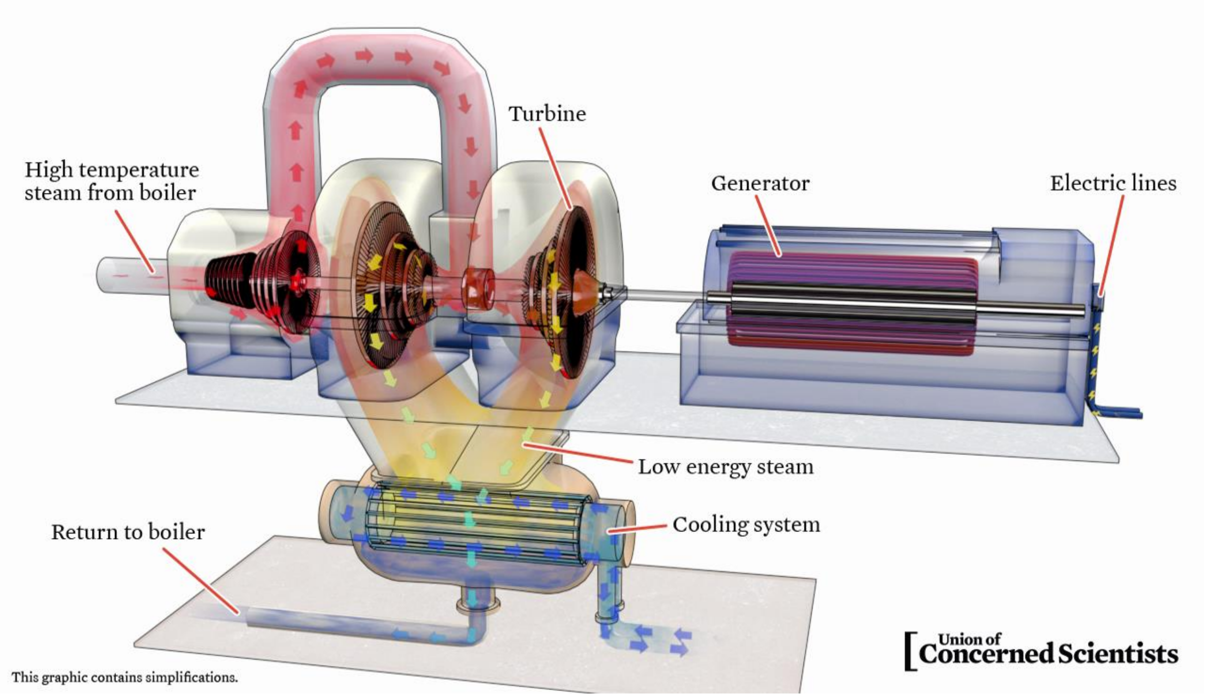


Figure 3: Steam Turbine & Generator System

BOILING WATER REACTORS

The Boiling Water Reactor (BWR) was originally designed by Allis-Chambers and General Electric. The General Electric design has survived, whereas, all Allis-Chambers units are now shutdown. The first commercial BWR plant was at Humboldt Bay (near Eureka, California). Other suppliers of the BWR design worldwide include ASEA-Atom, Kraftwerk Union and Hitachi. Commercial BWRs are operating in Finland, Germany, India, Japan, Mexico, Netherlands, Spain, Sweden, Switzerland, Taiwan and the U.S.

BWRs typically allow bulk boiling of the water in the reactor vessel. The operating temperature of the reactor is approximately 570 ^{0}F producing steam at a pressure of 1000 psi. Water is circulated through the reactor core picking up heat as it moves past the fuel assemblies. The water eventually is heated enough to be converted to steam. Steam separators that are positioned in the upper part of the reactor remove water from the steam before the steam passes through the main steam lines and through the turbine-generators. The steam after passing through the turbine, goes through the condenser which operates at vacuum. The steam in the condenser is cooled by cooled water pumped from an ocean, sea, lake or cooling tower.

The BWR is unique in that, the control rods, used to shutdown the reactor and maintain uniform power distribution across the core are inserted from the bottom by a high pressure hydraulically operated system. The BWR also has a torus (suppression pool) which is used to remove heat if an event occurs in which large quantities of steam are released from the reactor or to the reactor coolant circulation system.

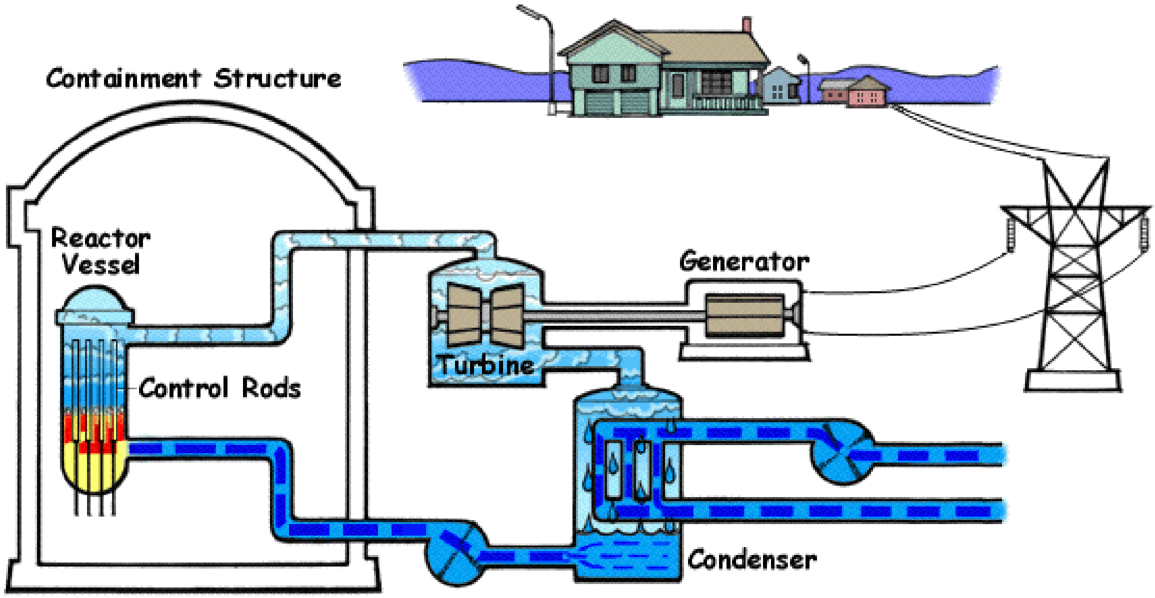


Figure 4: Boiling Water Reactor (BWR) System

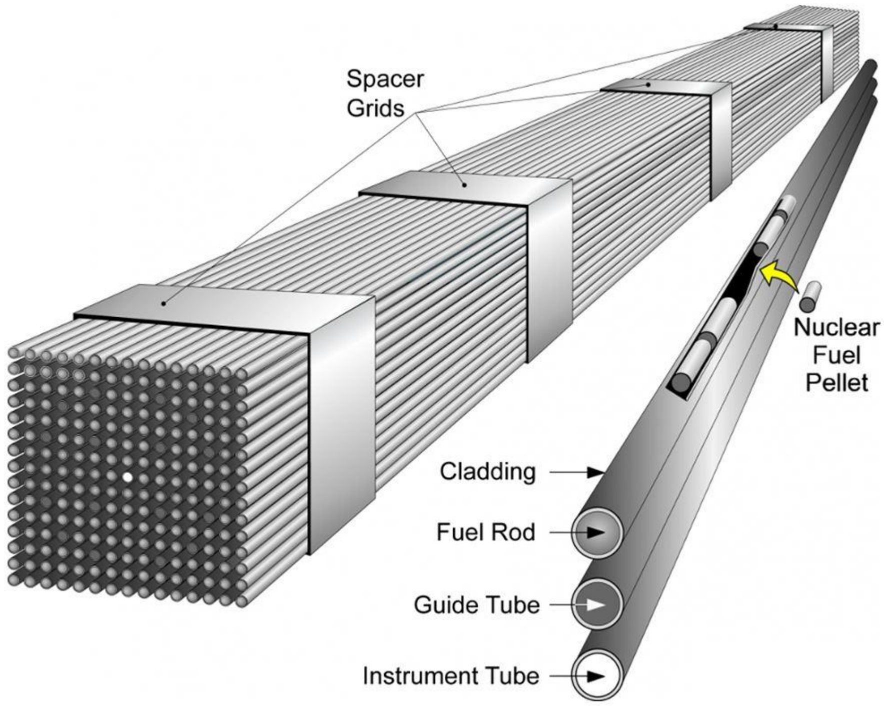


Figure 4: Reactor Fuel Assembly

CANDU REACTORS

The CANDU reactor is designed by Atomic Energy Canada Limited (AECL) as an alternative to other power designs which use slightly enriched uranium (2 to 5% U-235). The CANDU fuel contains pellets of natural uranium dioxide. Thus the CANDU is cheaper to fuel and can theoretically give higher lifetime capacity factors.

The CANDU design consists of a horizontal vessel which has tubes for the fuel rods and the cooling water, which is heavy water. Around these tubes, the heavy water acts as the moderator to slow down the neutrons from fast and high energy neutrons to slow, thermal neutrons. Heavy water (D_20) is much more efficient as a moderator than light water (H_20) and thus it allows the use of natural uranium as fuel.

As in the case with the pressurized water reactors, cooling pumps circulate the heavy water coolant through the reactor then to the steam generators in a closed loop. The heavy water moderator, which surrounds the fuel and cooling tubes within the reactor vessel, has a separate heat exchanger and circulation system for cooling the moderator. The CANDU reactor's cooling water tubes are pressurized to 1525 psi, lower than that for PWRs. CANDU reactors have world highest capacity factors and low fuel burnup.

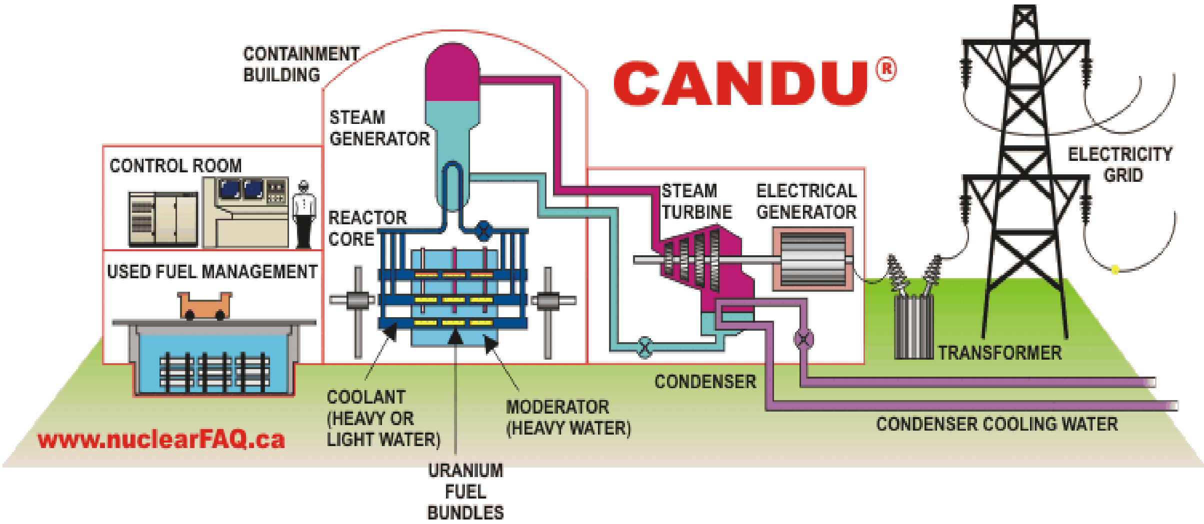


Figure 3: CANDU Reactor System

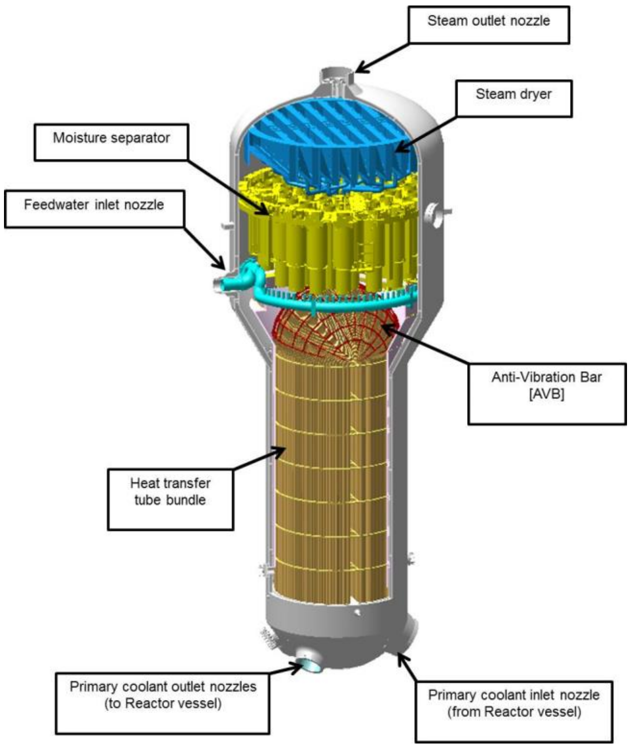


Figure 4: Steam Generator

GAS COOLED AND ADVANCE GAS COOLED REACTORS

In the Gas Cooled Reactors (GCR), the moderator is graphite. Carbon dioxide gas is circulated through the core at a pressure of about 230 psi to remove the heat from the fuel elements. The fuel consists of natural uranium metal with a cladding material which is an alloy of magnesium known as Magnox.

The newer Advanced Gas Cooled Reactor uses slightly enriched uranium dioxide clad with stainless steel. As with the GCR, carbon dioxide and graphite are the gas coolant and moderator respectively.

Two key advantages of Gas Cooled Reactors are, (1) Higher operating temperature with a higher thermal efficiency and (2) High resistance to accidents of the type possible with water cooled/moderated reactors.

The core of the High Temperature Gas Cooled Reactor (HTGR) consists of hexagonal shaped graphite blocks. Each graphite block has many fuel rod columns each consisting of eight fuel rods.

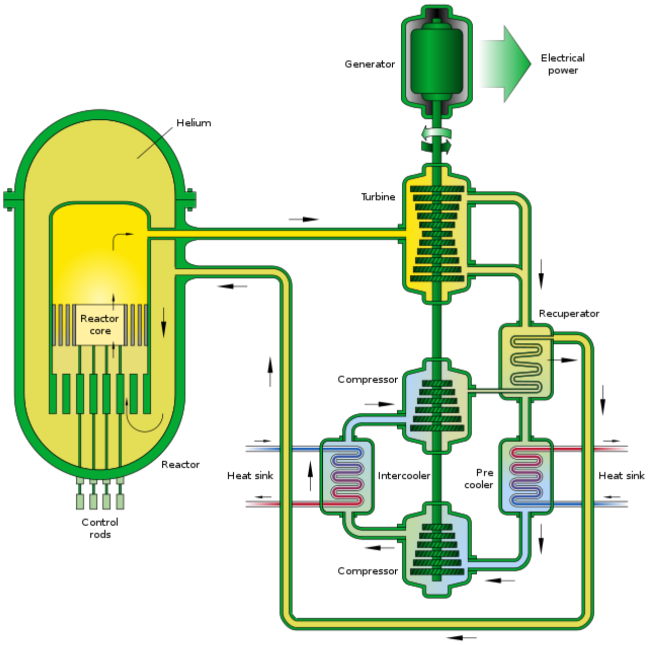


Figure 5: Gas Cooled Fast Reactor

LIQUID METAL COOLED REACTORS

Metal cooled reactors usually use liquid sodium or a combination of sodium and potassium in the liquid state as their coolant. Such reactors are usually referred to as, breeder reactors, fast reactors or fast breeder reactors.

An advantage of these reactors is that, the liquid metal has great heat transfer properties which allows the reactor to be operated at much lower pressures and at higher temperatures relative to most other reactor types. The enrichment of Uranium-235 use in these reactors is very low since Plutonium-239 or Uranium-233 is utilised as the main fissile nuclide in the nuclear fuel.

Currently, sodium has been universally chosen as the coolant for the modern Liquid Metal Fast Breeder Reactors (LMFBR). With an atomic weight of 23, sodium does not appreciably slow down neutrons by elastic scattering. Since sodium is an excellent heat transfer material, LMFBR can operate at high power density. This in turns means that, the core of the LMFBR can be comparatively small. Furthermore, because sodium has a much higher boiling point (892 ^{0}C) than water, reactor coolant loops can be operated at a higher temperature and at essentially atmospheric pressure without boiling, and no heavy pressure vessel is required. The high coolant temperature also leads to high temperature, high pressure steam and thus to high plant efficiency. Also, sodium unlike water, is not corrosive to many structural materials. Reactor components immersed in liquid sodium for years appear like new after the excess sodium has been washed off.

The melting point of sodum (97.8 ^{0}C) is considerably higher than room temperature. This makes the use of sodium undesirable in that, the entire coolant system must be kept heated at all times to prevent the sodium from solidifying. Sodium is also chemically very reactive. Hot sodium reacts violently with water and ignites when it comes with air emitting dense clouds of white sodium peroxide smoke. Additionally to some extent, sodium atoms absorb neutrons, even fast neutrons and therefore compete for the neutrons which should be used for sustain fission reaction. Sodium which passes through the LMFBR becomes radioactive. For this reason the reactors are inherently very tight systems that minimises the emission of radiation than Light Water Reactors (LWR).

The core of the LMFBRs consist of an array of fuel assemblies which are hexagonal stainless steel cans of 10 to 15 centimetres across and 3 or 4 meters in length. The cans contain fuel and fertile materials in the form of long pins. The fuel pins are stainless steel tubes that are 6 or 7 millimetres in diameter, containing pellets composed of a mixture of plutonium and uranium oxides. Depending on the reactor type, the fuel enrichment ranges from 15% to 35%.

The liquid sodium coolant enters through holes near the bottom of each assembly, passes upwards around the pins and then exits at the top of the core.

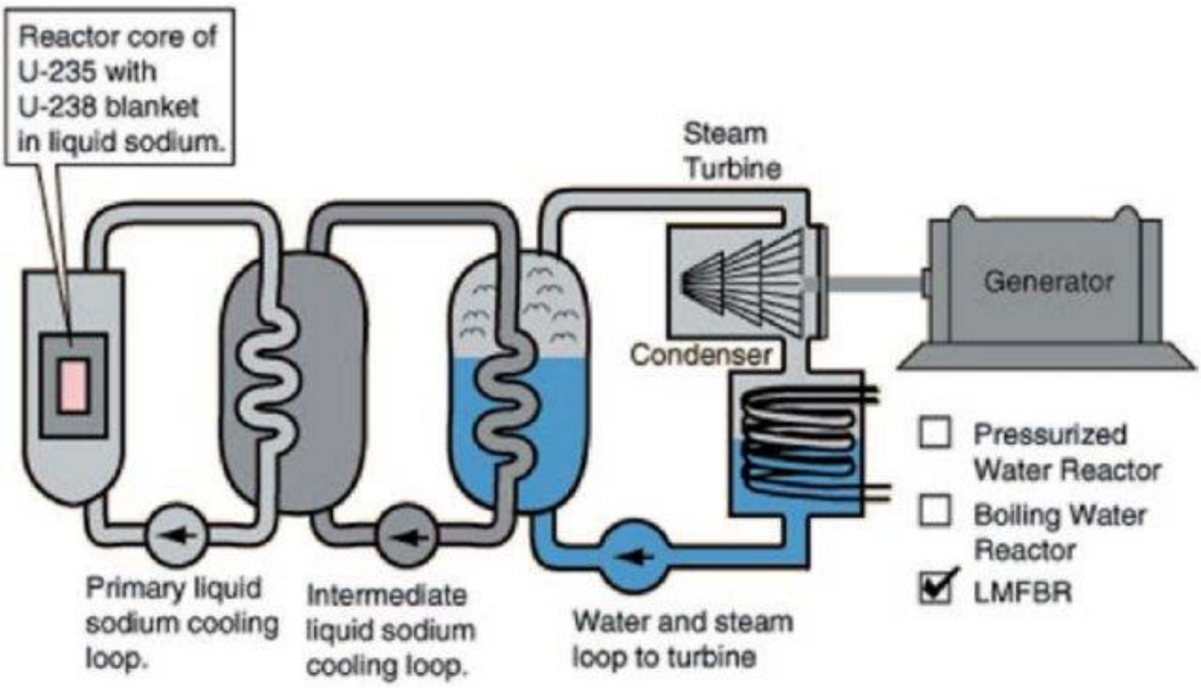


Figure 6: Liquid Metal Fast Breeder Reactor (LMFBR)

GENERATION FOUR NUCLEAR REACTORS

Generation Four Nuclear Reactors are innovative nuclear reactors expected to meet the energy needs of society in the future. In addition to meeting the energy need, this generation of reactors is designed to fulfill the concept of sustainable development. The concept of Generation IV nuclear reactors was developed by the Generation IV International Forum, originally consisting of 9 countries.

The concept of Generation IV reactors was launched in the United States in 2000 and the forum was established in 2001. The members of Gen IV forum consist of twelve countries (Canada, USA, China, France, Japan, Russia, South Korea, South Africa, Switzerland, Brazil, Argentina and United Kingdoms and the EU.

Over 100 experts evaluated around 130 reactor concepts, until just 6 were decided upon and determined as the Generation IV reactors. These reactors are planned to be deployed sometime in the 2030s

In designing and pursuing the reactors of the future, GIF has centered their goals around four broad areas.

1. **Sustainability**: Providing sustainable energy that meets clean air objectives, gives long-term availability of systems and effective fuel utilization for worldwide energy production. Also to minimize and manage waste, thereby improving protection for the public and the environment.
2. **Economics**: Reactors will have a clear life cycle cost advantage over other energy sources, along with less financial risk due to increased reliability.
3. **Safety**: The reactors will excel in safety and reliability; there will be very low likelihood of core damage, along with minimized severity in the case of an accident. Emergency response systems will be optimized and will not require offsite emergency response.
4. **Proliferation Resistance**: The reactor's use and processing of nuclear fuel will increase the assurance of materials being unattractive for theft and terrorism, along with a physical protection system to prevent the fuel from ending up in the wrong hands.

The 6 reactors determined by GIF to be the reactors of the future have clear advantages and technological advancements compared to reactors in use today, along with meeting the goals listed above. Most of the 6 systems employ a closed fuel cycle, meaning there will be less waste produced and more reused fuel. Their temperatures will be considerably higher than those in current use, allowing for higher efficiency of heat transfer and improved fuel use.

Figure 7 shows diagrams of the 6 innovative nuclear reactors and Figure 7(a) shows a diagram of the maximum temperatures that can be reached by some reactors.

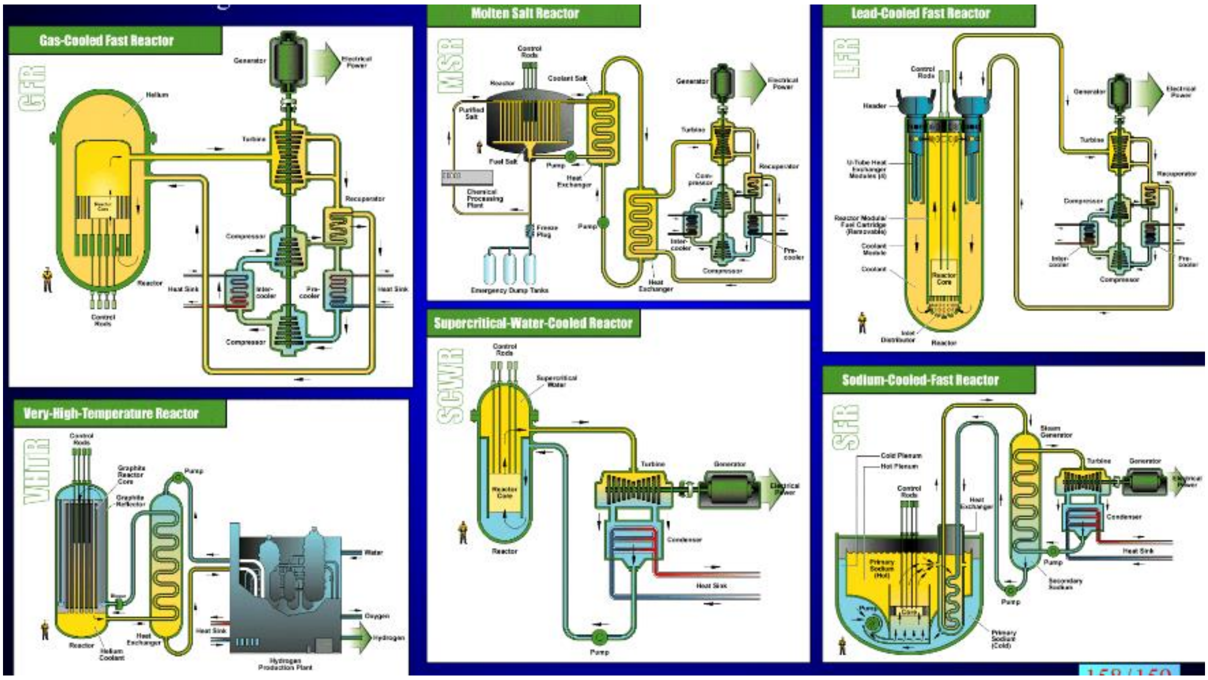


Figure 7: Generation Four Nuclear Reactor Concepts

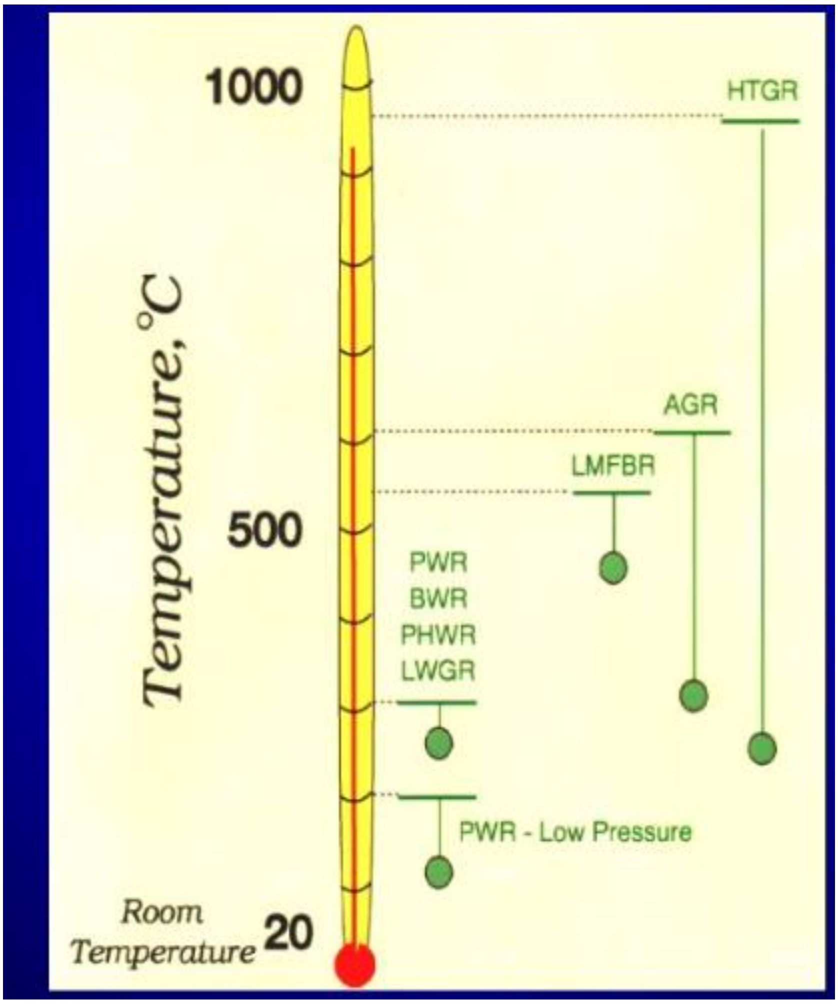


Figure 7(a): Reachable Temperature Range by Reactor Type

SMALL MODULAR REACTORS

As delays, costs and risk of devastating accidents mount on new large nuclear projects around the world, attention is shifting towards smaller alternatives which industry experts hope will push nuclear energy to the next generation of electricity. These small modular reactors (SMRs) are defined as nuclear power plants with a capacity of less than 300 megawatts. They are designed and produced in factories and are capable of being moved by train, truck or barge to its designated location. SMRs are not a new technological innovation or concept, in fact, small reactors are already used on nuclear submarines and in developing countries like India and Pakistan. However, with increasing interest in low cost, low risk energy sources and an influx of governmental support, SMR technology is now moving closer to wide adoption in a multitude of countries.

Since the invention of nuclear power, bigger has generally been seen to be better. Once a company had gone through the time and expense of securing a site along with planning approval and grid connections, most wanted to build as much capacity on that site as possible. However, SMRs promise the benefits of full-scale nuclear plants low costs and renewable energy without the significant cost and construction issues that conventional nuclear projects face.

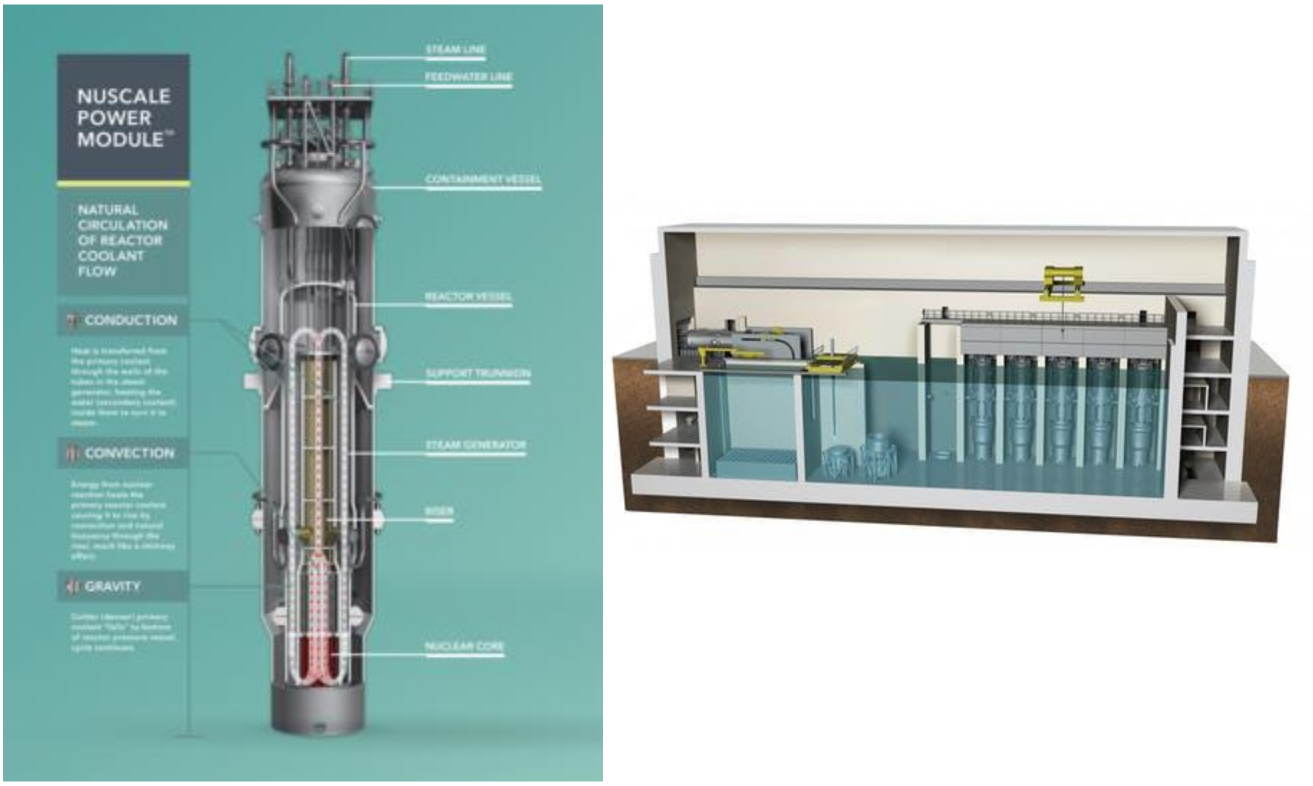


Figure 8: Small Modular Reactor, NuScale Reactor

The following is a list of SMRs being researched and/or developed in the United States:

1. Water-cooled reactors with small coated particle fuel without on-site refueling: AFPR (PNNL)

2. Sodium-cooled small reactor with extended fuel cycles: 4S (Westinghouse/ Toshiba); PRISM (GE); ARC (ARC)
3. Lead- or lead-bismuth-cooled small reactors with extended fuel cycles: HPM (Hyperion); LFR/SSTAR and its variations such as STARLM, STAR-H2, and SSTAR (ANL, LLNL and LANL); ENHS (UC Berkeley)
4. Gas-cooled thermal neutron spectrum reactor: MHR (GA); PBMR (Westinghouse); ANTARES (AREVA-U.S.)
5. Gas-cooled fast neutron spectrum reactor with extended fuel cycle: EM2 (GA)
6. Salt-cooled small reactor with pebble-bed fuel: PB-AHTR (UC Berkeley); SmAHTR (ORNL).

EVOLUTION OF NUCLEAR REACTORS

Generation 1 Reactors

Gen I refers to the prototype and power reactors that launched civil nuclear power. This generation consists of early prototype reactors from the 1950s and 1960s, such as Shippingport (1957–1982) in Pennsylvania, Dresden-1 (1960–1978) in Illinois, and Calder Hall-1 (1956–2003) in the United Kingdom. This kind of reactor typically ran at power levels that were "proof-of-concept." In the United States, Gen I reactors are regulated by the Nuclear Regulatory Commission (NRC) pursuant to Title 10, Code of Federal Regulations, Part 50 (10 CFR Part 50). The only remaining commercial Gen I plant, the Wylfa Nuclear Power Station in Wales, was scheduled for closure in 2010. However, the UK Nuclear Decommissioning Authority announced in October 2010 that the Wylfa Nuclear Power Station will operate up to December 2012.

Generation II Reactors

Gen II refers to a class of commercial reactors designed to be economical and reliable. Designed for a typical operational lifetime of 40 years. Prototypical Gen II reactors include pressurized water reactors (PWR), CANada Deuterium Uranium reactors (CANDU), boiling water reactors (BWR), advanced gas-cooled reactors (AGR), and Vodo-Vodyanoi Energetichesky Reactors (VVER). Gen II reactors in the United States are regulated by the NRC pursuant to 10 CFR Part 50. Gen II systems began operation in the late 1960s and comprise the bulk of the world's 400+ commercial PWRs and BWRs. These reactors, typically referred to as light water reactors (LWRs), use traditional active safety features involving electrical or mechanical operations that are initiated automatically and, in many cases, can be initiated by the operators of the nuclear reactors. Some engineered systems still operate passively (for example, using pressure relief valves) and function without operator control or loss of auxiliary power.

Most of the Gen II plants still in operation in the West were manufactured by one of three companies: Westinghouse, Framatome (now part of AREVA, and General Electric (GE). The Korean Standard Nuclear Power Plant (KSNP), which is based on Gen II technology developed by Combustion Engineering (now Westinghouse) and Framatome (now AREVA), is now recognized as a Gen II design.

Gen II plants designs require relatively large electrical grids, have a defined safety requirement based on Western safety standards, and produce significant quantities of used fuel that require ultimate disposition in a high-level waste repository or reprocessing as part of a partially or fully closed fuel cycle.

The frequency of core damage to Gen II reactors is reported to be as high as one core damage event for every 100,000 years of operation (10−5 core damage events per reactor year for the BWR(4)).

Generation III Reactors

Gen III nuclear reactors are essentially Gen II reactors with evolutionary, state-of-the-art design improvements. These improvements are in the areas of fuel technology, thermal efficiency, modularized construction, safety systems (especially the use of passive rather than active systems), and standardized design. Improvements in Gen III reactor technology have aimed at a longer operational life, typically 60 years of operation, potentially to greatly exceed 60 years, prior to complete overhaul and reactor pressure vessel replacement. Confirmatory research to investigate nuclear plant aging beyond 60 years is needed to allow these reactors to operate over such extended lifetimes. Unlike Gen I and Gen II reactors, Gen III reactors are regulated by NRC regulations based on 10 CFR Part 52.

The Westinghouse 600 MW advanced PWR (AP-600) was one of the first Gen III reactor designs. On a parallel track, GE Nuclear Energy designed the Advanced Boiling Water Reactor (ABWR) and obtained a design certification from the NRC. The first of these units went online in Japan in 1996. Other Gen III reactor designs include the Enhanced CANDU 6, which was developed by Atomic Energy of Canada Limited (AECL); and System 80+, a Combustion Engineering design. Only four Gen III reactors, all ABWRs, are in operation today. No Gen III plants are in service in the United States.

Core damage frequencies for Gen III and Gen III+ reactors are reported to be lower than those of Gen II reactors, in the range of one core damage event for every 15–20 million years of operation (6×10^{-7} core damage events per reactor year). These standardized designs are intended to reduce maintenance and capital costs. The capital cost requirements are highly dependent on country and international material, labor, and other considerations.

Generation III+ Reactors

Gen III+ reactor designs are an evolutionary development of Gen III reactors, offering significant improvements in safety over Gen III reactor designs certified by the NRC in the 1990s. In the United States, Gen III+ designs must be certified by the NRC pursuant to 10 CFR Part 52. Examples of Gen III+ designs include:

1. VVER-1200/392M Reactor of the AES-2006 type
2. Advanced CANDU Reactor (ACR-1000)
3. AP1000: based on the AP600, with increased power output
4. European Pressurized Reactor (EPR): evolutionary descendant of the Framatome N4 and Siemens Power Generation Division KONVOI reactors
5. Economic Simplified Boiling Water Reactor (ESBWR): based on the ABWR
6. APR-1400: an advanced PWR design evolved from the U.S. System 80+, originally known as the Korean Next Generation Reactor (KNGR)
7. EU-ABWR: based on the ABWR, with increased power output and compliance with EU safety standards
8. Advanced PWR (APWR): designed by Mitsubishi Heavy Industries (MHI)12

9. ATMEA I: a 1,000–1,160 MW PWR, the result of a collaboration between MHI and AREVA.

Manufacturers began development of Gen III+ systems in the 1990s by building on the operating experience of the American, Japanese, and Western European LWR fleets. Perhaps the most significant improvement of Gen III+ systems over second-generation designs is the incorporation in some designs of passive safety features that do not require active controls or operator intervention but instead rely on gravity or natural convection to mitigate the impact of abnormal events. The inclusion of passive safety features, among other improvements, may help expedite the reactor certification review process and thus shorten construction schedules.

These reactors, once on line, are expected to achieve higher fuel burnup than their evolutionary predecessors (thus reducing fuel consumption and waste production).

Generation IV Reactors

Conceptually, Gen IV reactors have all of the features of Gen III+ units, as well as the ability, when operating at high temperature, to support economical hydrogen production, thermal energy off-taking, and perhaps even water desalination. In addition, these designs include advanced actinide management Gen IV reactors include:

1. High temperature water-, gas-, and liquid salt–based pebble bed thermal and epithermal reactors.

2. Liquid metal–cooled reactors and other reactors with more-advanced cooling. One such design is the Power Reactor Innovative Small Module (PRISM), a compact modular pool-type reactor developed by GE-Hitachi with passive cooling for decay heat removal.

3. Traveling wave reactors that convert fertile material into fissile fuel as they operate, using the process of nuclear transmutation being developed by TerraPower. This type of reactor is also based on a liquid metal primary cooling system. It is also being designed with passive safety features for decay heat removal, and has as a major design goal minimization of life cycle fuel costs by both substantially increasing the burnup percentage and internally breeding depleted uranium.

4. Hyperion Power Module (25 MW module). According to Hyperion, uranium nitride fuel would be beneficial to the physical characteristics and neutronics of the standard ceramic uranium oxide fuel in LWRs.25 Gen IV reactors are two-to-four decades away, although some designs could be available within a decade. As in the case of Gen III and Gen III+ designs in the United States, Gen IV designs must be certified by the NRC pursuant to 10 CFR Part 52, based on updated regulations and regulatory guides.

Generation IV reactors under development include the following,

1. Gas-cooled fast reactors: Uses Helium as coolant and operate at a high pressure and a temperature of 850 ^{0}C.
2. Lead- cooled fast reactors: Uses lead or lead-bismuth as coolant and operate at low pressure and a temperature ranging between 480 and 800 ^{0}C.
3. Molten salt fast reactors: Uses Fluoride salt as coolant and operate at a low pressure and a temperature ranging between 700 and 800 ^{0}C.

4. Molten salt reactor, Advanced high temperature reactors: Uses Fluoride salt as coolant and operating with a temperature ranging between 750 and 1000 ^{0}C.
5. Sodium cooled fast reactors: Uses sodium as coolant and operate at a low pressure and a temperature of 550 ^{0}C.
6. Travelling wave reactors: Uses sodium as coolant and operate at a low pressure and a temperature of 510 ^{0}C.
7. Supercritical water cooled reactors: Uses water as coolant and operate at a very high pressure and a temperature ranging between 510 and 625.
8. Very high temperature gas reactors: Uses Helium as coolant and operate at a high pressure and a temperature ranging between 900 and 1000 ^{0}C.

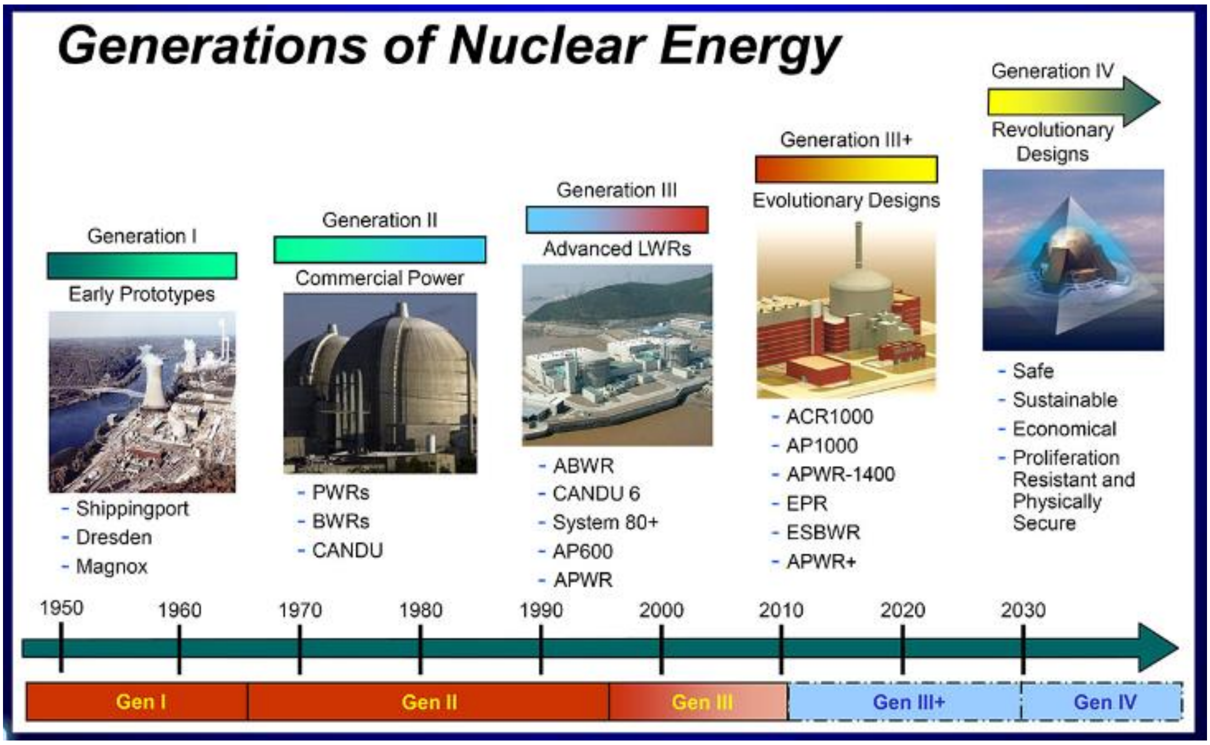


Figure 8: Evolution of Nuclear Reactors

1.3 Accidents in the Nuclear Power Industry and their Impacts

The slowdown in nuclear power expansion was already well under way when a serious but non-fatal accident occurred in 1979 at the power plant at Three Mile Island in Harrisburg, Pennsylvania. By coincidence, the film The China Syndrome, which describes a near meltdown at a nuclear plant, was released just 12 days before the accident, and the similarities between the film's plot and the real events that took place severely damaged the nuclear industry's image.

After 1979, no nuclear plants were ordered in the United States, dozens of projects were cancelled, and investment money dried up. The downturn also affected Europe. In referenda in Austria and Sweden, voters rejected nuclear power, and several reactors were cancelled.

Research by WINS has indicated that the Three Mile Island incident was responsible for a doubling of the cost of nuclear-generated power worldwide in the following years.

1.3.1 Fukushima Daiichi Accident

The earthquake and tsunami that struck eastern Japan on March 11, 2011, caused a serious accident at the Fukushima Dai-ichi nuclear power plant on the northeastern coast of Japan.

The earthquake cut off external power to the reactors. tsunami, which reached levels more than twice as high as the plant was designed to withstand, disabled backup diesel generators, crippling the reactor cooling systems. Battery power was quickly exhausted, and overheating fuel in the plant's operating reactor cores led to hydrogen explosions that severely damaged three of the reactor buildings. Fuel in three of the reactor cores melted, and radiation releases from the damaged reactors contaminated a wide area surrounding the plant and forced the evacuation of nearly half a million residents.

The Fukushima Daiichi reactors are GE boiling water reactors (BWR) of an early (1960s) design supplied by GE, Toshiba and Hitachi, with what is known as a Mark I containment. Reactors 1-3 came into commercial operation 1971-75.

1.3.2 The Chernobyl Accident

The nuclear industry's problems were compounded by the reactor explosion at Chernobyl in 1986, which caused a number of deaths and contaminated large parts of Ukraine and Belarus. Chernobyl is considered the world's worst nuclear disaster to date. It occurred on April 26, 1986 in Chernobyl, Ukraine (former Soviet Union), when a sudden surge in power during a reactor systems test resulted in an explosion and fire that destroyed Unit 4. Massive amounts of radiation escaped and spread across the western Soviet Union and Europe. As a result of the disaster, approximately 220,000 people had to be relocated from their homes.

Unit 4 was to be shut down for routine maintenance. A test was conducted to determine the plant equipment's ability to provide sufficient electrical power to operate the reactor core cooling system and emergency equipment during the transition period between a loss of main station electrical power supply and the start-up of the emergency power supply. Workers did not implement adequate safety precautions or alert operators to the electrical test's risks. This lack of awareness led the operators to engage in actions that diverged from safety procedures. Consequently, a sudden power surge resulted in explosions and nearly complete destruction of the reactor. The fires that broke out in the building contributed to the extensive radioactive releases. A variety of estimates from the 1990s place the costs of the accident at hundreds of billions of dollars over two decades.

Some of the reasons for the costs resulting from the accident include:

- Direct damage
- Expenditures related to recovery and mitigation
- Resettlement of people
- Social protection and health care for the affected population
- Research on environment, health and the production of clean food
- Radiation monitoring

- Indirect losses due to removing agricultural lands and forests from use and the closing of agricultural and industrial facilities
- Cancellation of the nuclear power program in Belarus
- Additional energy costs due to loss of power from Chernobyl

A year after the Chernobyl incident, Italy decided to shut down its four power plants. Germany, too, decided to phase out its nuclear power stations.

In the years after the Chernobyl accident, there was increased competition in the energy market and hence lower energy prices. Although nuclear power stations are relatively cheap to run, their high front-load costs place them at a disadvantage compared to other energy industries at the time and thus the nuclear energy industry became unattractive. (The high capital cost in the nuclear power industry was as a result of the need to ensure high safety standards and more improved nuclear technology than existed earlier.

1.3.3 The Three Mile Island Accident

The partial meltdown at Three Mile Island Unit 2 is considered the most serious nuclear accident in U.S (Middletown, Pennsylvania, USA**,** March 28, 1978**)** history, although it resulted in only small radioactive releases.

The accident began with failures in the non-nuclear secondary system, followed by a human-operated relief valve in the primary system that stuck open, which allowed large amounts of nuclear reactor coolant to escape. Plant operators' initial failure to correctly identify the problem compounded it. In particular, a hidden indicator light led to an operator manually overriding the automatic emergency cooling system because he mistakenly believed that too much coolant water in the reactor had caused the steam pressure release. Eventually the reactor was brought under control.

1.3.4 The Enrico Fermi Unit 1 Accident

Coolant flow blockage in two fuel channels led to the partial meltdown of two fuel assemblies at Fermi Unit 1 in the Frenchtown Charter Township, Michigan, USA**,** on October 5, 1966.

Fermi Unit 1 was the nation's first and only commercially operating liquid metal fast breeder reactor. Vibrations caused a component within the reactor vessel to loosen, which blocked coolant flow when hydrodynamic forces carried it up the fuel subassemblies' inlet nozzle. Workers did not notice what had occurred until core temperature alarms sounded. Several fuel rod subassemblies reached temperatures of up to 700 degrees Fahrenheit, causing them to melt. After the reactor was shut down for repairs, it was returned to partial operation periodically until 1972, but it was never again fully operational. It was officially decommissioned in 1975.

1.3.5 SL-1 Accident

The withdrawal of a single control rod caused a catastrophic power surge and steam explosion at the SL-1 boiling water reactor (Idaho Falls, Idaho, USA**,** January 3, 1961)**.**

On January 3, 1961, workers were in the process of reattaching to their drive mechanisms control rods they had disconnected earlier that day to enable test equipment to be inserted in the reactor core. They lifted the central control rod 20 inches, instead of the four inches that was required. This error caused the reactor to go critical and its power to surge 6,000 times higher than its normal level in less than a second. As a result, nuclear fuel vaporized and a steam bubble was created. The steam bubble expanded so quickly that it pushed water above it against the reactor vessel, which caused it to jump out of its support structure. It hit an overhead crane and then returned to the reactor vessel. In the process, all of the water and some of the fuel was released from the reactor vessel. All three workers on duty received lethal doses of radiation, in addition to trauma from the explosion.

1.3.6 Sodium Reactor Experiment Accident

A partial meltdown occurred at the Sodium Reactor Experiment (SRE) **(**Los Angeles, California, USA**,** July 1959**)** due to cooling flow blockage that caused the reactor core to overheat.

The Sodium Reactor Experiment experienced extensive fuel damage during a power run. Thirteen of forty-three fuel elements overheated when the cooling flow provided by the liquid sodium was blocked by tetralin, an oil-like fluid which had leaked into the primary sodium loop during prior power runs. This overheating caused the reactor core to fail. Fission products were released from the damaged fuel into the primary sodium loop. Some of the fission products leaked from the primary sodium loop into the high bay area, a region inside the building housing the reactor. Other fission products flowed with the helium cover gas over the liquid sodium in the reactor pool to gaseous storage tanks. Fission products from the high bay area and from the gaseous storage tanks were processed through the filters of a ventilation system and discharged to the atmosphere.

1.3.7 The Windscale Accident

Windscale Unit 1's core in Cumberland (now Cumbria), UK**,** on October 10, 1957 caught fire and melted, which led to the release of large amounts of radioactivity to the surrounding area.

Before the accident, Unit 1 was activated to release built-up energy in the graphite of the core. The fuel was cooler than the normal operating temperature and was warming more slowly than expected. A second release led to a higher temperature than workers expected. Eventually the temperature was more than 750 degrees Fahrenheit, so air was vented to cool it. The reactor caught fire, igniting an estimated 11 tons of uranium. Workers first used carbon dioxide to try to put out the fire, but that strategy failed. Next they used water, which eventually succeeded. It took workers a total of three days to put out the fire. In the meantime, radiation escaped through the chimney and contaminated much of the surrounding area and reached as far as mainland Europe. More than 200 cancer deaths are attributed to the disaster, which is considered to have been the worst to occur in the West.

It is clear from literature that, all these events in the history of nuclear reactors involved the very first generation of nuclear reactors. Modern reactors are built taking into consideration all previous experiences in the operation of reactors and are very robust to entertain the possibilities of the occurrence of such previous accidents/events.

1.4 Nuclear Renaissance and the Future of Nuclear Power

Since about 2001 the term "nuclear renaissance" has been used to refer to a possible nuclear power industry revival. This is being driven by rising fossil fuel prices and new concerns about meeting greenhouse gas emission limits.

The International Energy Outlook Reference Case for 2013 predicts that world energy consumption will grow by over 50% by 2040 and that worldwide electricity generation from renewables and nuclear power will dominate the energy increases. As concerns about energy security and greenhouse gas emissions support the development of new nuclear generating capacity, predictions are that nuclear will almost double by 2040. This means that nuclear energy production has been forecast to increase from 2.6 trillion kilowatt-hours in 2010 to 5.5 trillion kilowatt-hours in 2040.

Factors taken into account in these projections include the consequences of the March 2011 disaster at Fukushima Daiichi, Japan; planned retirements of nuclear capacity in European countries belonging to the Organisation for Economic and Cooperation Development (OECD); and continued strong growth of nuclear power in non-OECD Asia. (Almost 40% of the global net increase in nuclear capacity is expected to be in China.) Germany and Switzerland have announced plans to phase out or shut down their operating reactors by 2022 and 2034, respectively.

A number of small, innovative power reactor designs are currently under development. These have features more suited to conditions in developing countries, such as lower power levels, life-time or long-life fuel cores, and modular construction and operation. The lower capital costs and simplified operational requirements of these reactors could make nuclear power more accessible to a number of developing countries.

Over the short term, the low price of natural gas, including hydraulic fracturing (fracking), which extracts natural gas from harder to access unconventional sources trapped in rock formations such as shale gas, and the impact of increasing capacities of subsidised renewable energy sources are expected to negatively impact nuclear growth prospects in some regions of the developed world. Moreover, the on-going financial crisis continues to present challenges for capital-intensive projects such as nuclear power.

The overall conclusion is that the incident at the Fukushima Daiichi nuclear power plant will cause temporary delay of some nuclear power plant construction. However, in the long run, the underlying fundamentals of population growth and demand for electricity in the developing world, as well as climate change concerns, security of energy supply and price volatility for other fuels (one reason natural gas prices are low is that macroeconomic conditions are currently depressing demand) will mean that nuclear generating capacity will continue to play an important role in the energy mix.

1.4 Inherent Safety in Nuclear Reactor Designs

Safety of a nuclear power plant is conditioned by failure free and reliable operation of all its facilities and systems that prevents occurrence of an accident or removing consequences of failures, retaining radioactive materials in defined areas, and preventing their spreading into the environment in case of their release. The present level of safety of nuclear reactors ensures that all systems are able to cope with failures separately without endangering the population and the environment.

Basic principle of safety of nuclear power plants is based on a defence in depth principle. The defence in depth consists of 4 physical barriers and 5 levels of protection. The defence in depth principle is designed to cater for potential human errors and equipment failures. It concentrates on several protection barriers, including those preventing release of radioactive substances into the environment. The principle covers also protection of the barriers themselves and other measures for protection of the population and the environment against damage if these barriers are not fully effective.

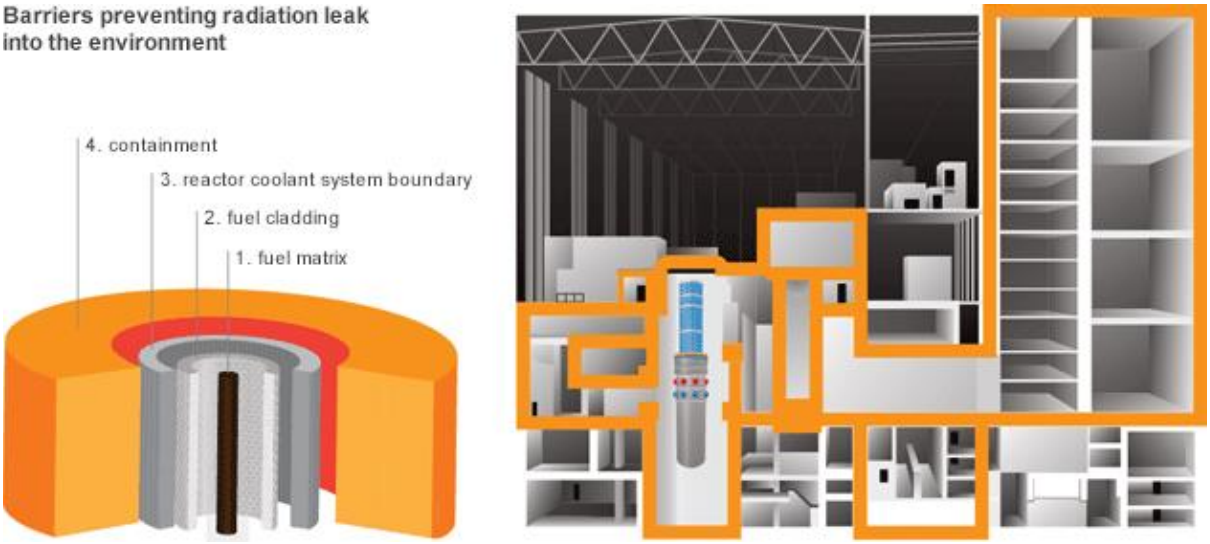


Figure 9: Physical Safety Barriers of a Nuclear Power Plant

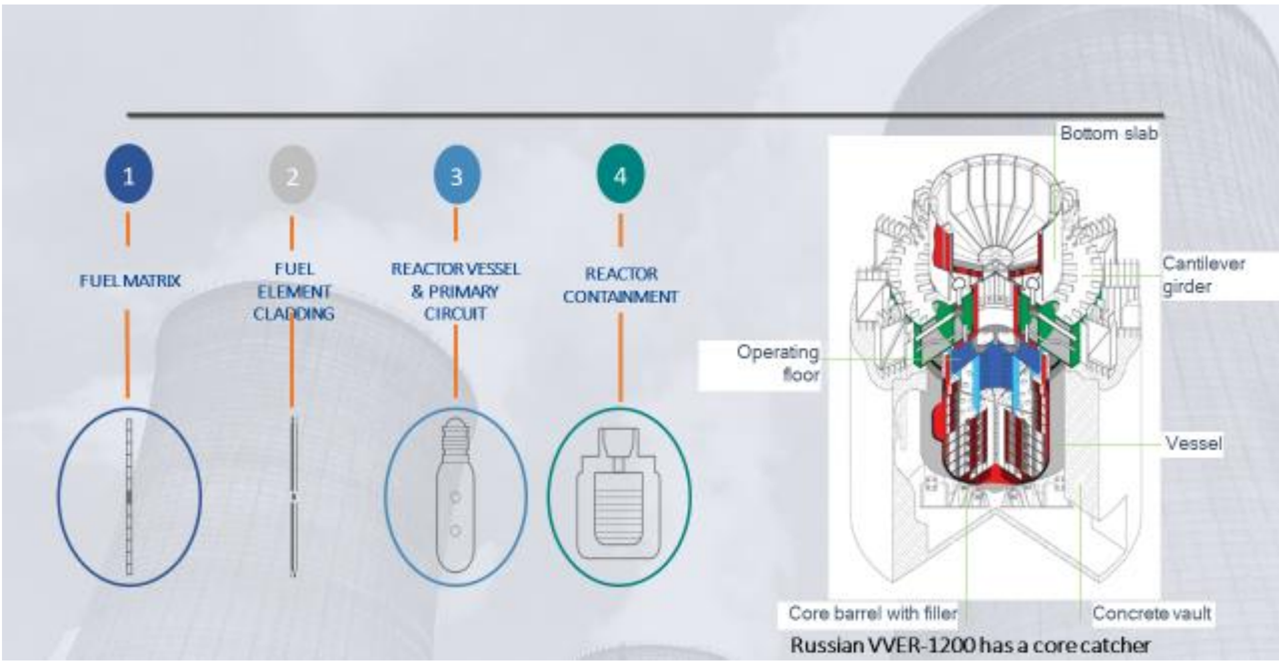


Figure 10: The Four Physical Barriers of a Nuclear Power Plant

The reliability of each of these barriers is very high and hence the probability of simultaneous damage of all three barriers and release of radioactive material into the environment is very low.

1. **The first barrier** consists of crystal fuel matrix in form of ceramic tablets or pellets.
2. **The second barrier** is fuel cladding – hermetically sealed tube made out of zirconium alloys.
3. **The third barrier** is a hermetically sealed primary circuit pressure system with the reactor pressure vessel preventing release of coolant with radioactive substances into the environment at all anticipated temperatures and pressures.

4. **The fourth barrier** is the containment – 1.5 m thick steel-concrete envelope, retaining radioactive substances that could be released through potential damage of the first three barriers.

Modern nuclear power plants are built to be so robust to withstand such activities as shown in Figure 11.

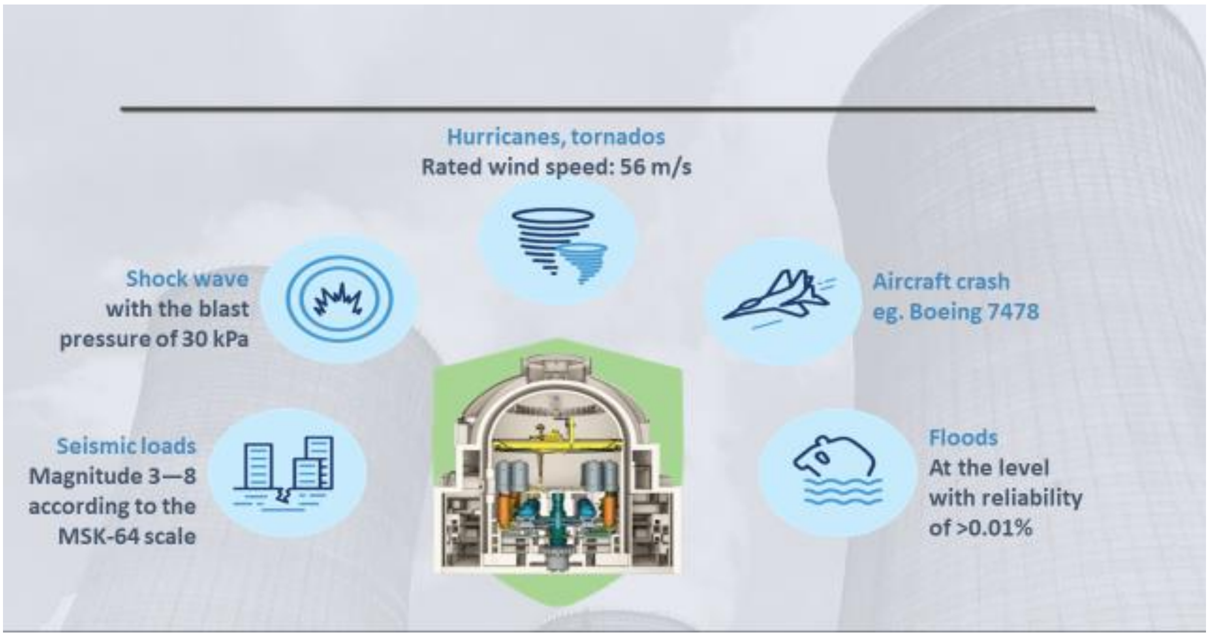


Figure 11: Robustness of Nuclear Power Reactors

CHAPTER TWO: Nuclear Fuel Cycle and Technology

In this chapter, we present literature on the steps in the nuclear fuel cycle, including how materials are created, stored, recycled and reprocessed, and the vital ways in which nuclear technology is making a contribution to industry, medicine, agriculture and research. We expect that readers understand the key features of the nuclear fuel cycle and the application of nuclear technology

2.1 Nuclear Fuel Cycle

The various processing activities and facilities that support the operation of nuclear reactors and are associated with the production of electricity from nuclear reactions are referred to collectively as the nuclear fuel cycle.

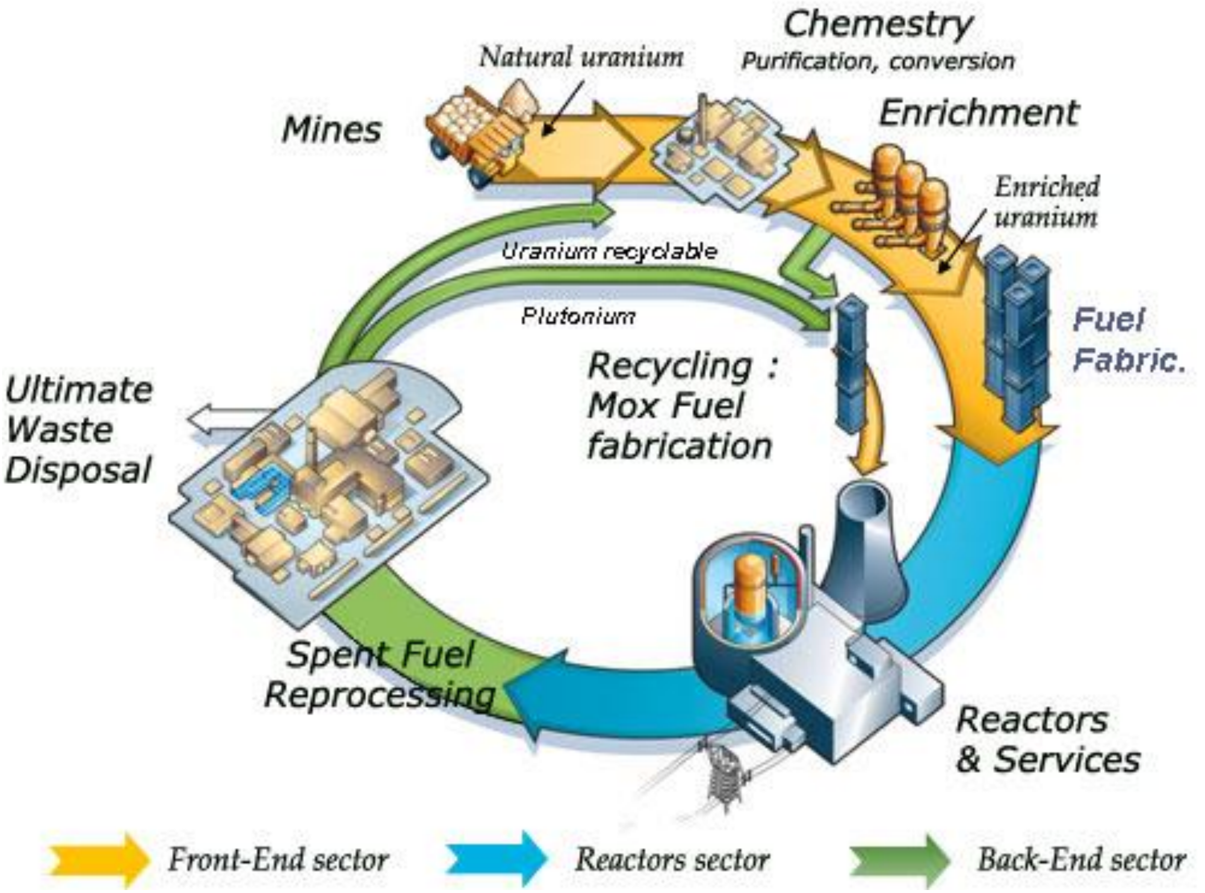


Figure 12: Nuclear Fuel Cycle

The nuclear fuel cycle starts with the mining of uranium and ends with the disposal of nuclear waste. Some countries have decided to store and dispose of the reactor fuel after it has been discharged; others have decided to recycle the used (spent) nuclear fuel and extract the plutonium it contains so that it can be fabricated into new fuel.

Components of Fuel Cycle processes include the following,

1. Mining
2. Milling
3. Refining
4. Conversion

5. Enrichment
6. Fuel Fabrication
7. Reactors
8. Reprocessing
9. Recycle Fuel Fabrication
10. Waste Storage

2.1.1 Mining and Milling of Uranium Ore

Uranium occurs in many locations throughout the world in very low concentrations. One of the more common uranium minerals is pitchblende (U_3O_8). Although uranium concentration in pure form of the pitchblende may range from 90% to 75%, they typically contain 0.2% of uranium.

The two most commonly used methods of mining uranium are open pit mining and underground mining. A third method known as solution or in-situ mining is utilized on limited basis.

In in-situ mining, water is circulated through very porous ore-body to dissolve the uranium and bring it to the surface. The uranium is then recovered from the solution as is typically done in a conventional mill.

A uranium mill is a chemical plant that extracts uranium from mined ore. At conventional mills, the ore arrives in trucks and is crushed, ground and leached. The uranium is then removed from this solution, precipitated and dried.

Milling produces a uranium oxide concentrate that is then shipped from the mill. This is sometimes referred to as "yellowcake" and generally contains more than 80% uranium. The process of milling uranium ore consist of the following stages,

1. Feed Preparation
2. Leaching
3. Solid-Liquid Separation
4. Concentration and Purification
5. Precipitation and Drying of product

2.1.2 Conversion and Enrichment

Yellow cake that is obtained from the uranium mill typically contains 70% to 80% uranium. This is still in the form of natural uranium in that only 0.71% of the uranium is Uranium-235 which is the isotope needed for fission reactions. Therefore before the yellow cake could be used for the fabrication of nuclear fuel, the concentration of the Uranium-235 must be increased through processes known as conversion and enrichment.

The two most widely enrichment processes, namely, gaseous diffusion and gas centrifuge require that the uranium be in a gaseous state. To achieve this, the yellow cake is refined and converted into Uranium Hexafluoride (UF6).

UF6 is the only uranium compound that exists as a gas at a suitable condition (atmospheric pressure and normal room temperature) for processing. During the conversion, impurities are removed and the uranium is combined with fluorine to create the UF6 gas. The UF6 is then pressurised and cooled to a liquid which is then collected into large metal cylinder where it solidifies after cooling. The UF6 cylinder, with the UF6 in solid form, is then shipped to an enrichment plant.

Natural uranium primarily consists of a mixture of two isotopes of uranium. Only 0.7% of natural uranium is "fissile" or capable of undergoing fission in a normal reactor. Fission is the process by which energy is produced in a nuclear power reactor. The fissile isotope of uranium is uranium-235 (235U); the remainder is mostly uranium-238 (238U) which is a fertile isotope. In the most common types of nuclear reactors, a higher-than-natural concentration of 235U is required. The enrichment process produces this higher concentration, typically between 3.5% and 5% 235U.

This is done by separating gaseous uranium hexafluoride into two streams. One is enriched to the required level, known as low-enriched uranium (LEU), while the other, called tails, is very low in 235U.

Two enrichment processes are in large-scale commercial use: gaseous diffusion and gas centrifuge enrichment. Both use uranium hexafluoride as feed and the physical properties of molecules, specifically the 1% mass difference, to separate isotopes. Other enrichment processes that are worth mentioning are, atomic vapor laser isotope separation, aerodynamic vortex tube, aerodynamic separation nozzle, chemical exchange, ion exchange, laser molecular separation, and electromagnetic isotope separation.

A small number of reactors, principally those used for research and the production of medical isotopes, use fuel that is in the high enriched uranium range (HEU; above 20% 235U). In the 1970s, over 150 research reactors worldwide used HEU fuels; today the number has significantly decreased because of international programmes created to reduce the use of HEU. (HEU can be used to make a nuclear explosive device, unlike low enriched uranium.) Many of these reactors have now been converted to run on low enriched uranium, and determined efforts are being made to convert the remaining reactors wherever it is technically and economically feasible to do so.

Gaseous Diffusion

The gaseous diffusion enrichment process is a much older, more inefficient technology; consequently, it is now being phased out. Gaseous diffusion enrichment requires that the solid uranium hexafluoride from the conversion process be heated in its container until it becomes a liquid. The UF6 gas is then slowly fed into the plant's pipelines, where it is pumped through special filters. Holes in the filters are designed so that the lighter UF6 gas molecules diffuse faster through the filters than the heavier UF6 gas does. One filter isn't enough to carry out this process; it requires many hundreds of filters in a chain before the UF6 gas contains enough uranium-235 to be used in reactors.

At the end of the process, the enriched UF6 gas is condensed back into a liquid that is poured into containers. The UF6 is then allowed to cool and solidify before it is transported to fuel fabrication facilities, where it is turned into fuel assemblies for nuclear power reactors. Diffusion plants are typically huge buildings and require enormous amounts of electricity to operate.

Gas Centrifuge

The gas centrifuge uranium enrichment process uses a large number of rotating cylinders held under vacuum. The cylinders are interconnected to form cascades; each part of the cascade is called a stage. In this process, UF6 gas is fed into the first stage of centrifuges, each containing a rotor. When the rotors are spun rapidly, at up to 70,000 rpm, the heavier molecules increase in concentration toward the cylinder's outer edge. There is a corresponding increase in concentration of lighter molecules near the centre. Eventually, enriched and depleted uranium hexafluoride are drawn from the cascade at the desired assays and go into chilled storage containers for transport to the fuel fabrication plant.

Fuel Fabrication

Most of the fuel used for nuclear power reactors uses low enriched UF6. Reactor fuel generally consists of ceramic pellets. These are formed from pressed uranium oxide that is sintered at high temperature. The pellets are then encased in metal tubes to form fuel rods, which are then arranged into a fuel assembly for introduction into a reactor. The fuel assemblies loaded into reactors are typically about 4 metres in length and weigh about 500 kgs. The majority of the materials at a fuel fabrication facility are in a solid form (as uranium oxide) that is very difficult to disperse and has low radioactivity.

2.1.3 Nuclear Power Generation

Inside a nuclear reactor, the nuclei of uranium-235 atoms split (fission); in the process, they release energy. This energy is used to heat water and turn it into steam in the same way that the burning of coal, gas or oil is used as a source of heat in a fossil fuel power plant. The steam is used to drive a turbine connected to a generator that produces electricity. Some of the uranium-238 in the fuel is turned into plutonium in the reactor core; other radioactive isotopes are also created.

2.1.4 Nuclear Waste Management and Disposal

Spent fuel

Over time, the concentration of fission products in the reactor fuel increases to the point where it is no longer practical to continue to use the fuel. After 18 to 24 months, the spent fuel is removed from the reactor. The amount of energy produced from a fuel bundle varies with the type of reactor and the policy of the reactor operator. Typically, the energy produced from fuel made from one tonne of natural uranium is equivalent to the burning of over 20,000 tonnes of coal or 8.5 million cubic metres of gas.

Storage

When removed from a reactor, spent fuel emits both radiation and heat. It is unloaded into a water-filled storage pond next to the reactor to allow the radiation levels and heat to decrease. In the ponds, the water shields the radiation and absorbs the heat. Spent fuel is kept in such pools for several months to several years.

Figure 12(a): Storage Pool for Spent Nuclear Fuel

Depending on policies in particular countries, some spent fuel may be transferred to central storage facilities. Ultimately, spent fuel must either be reprocessed or prepared for permanent disposal. Some countries use interim storage, which involves removing the fuel from wet pond storage and placing it in large, dry storage casks.

Most of the radioactive wastes are classified as low or medium level waste and are characterised by relatively short half-lives. Storage of such radioactive wastes until they decay does not involve any technological challenges for current engineering. An example of such a facility is depicted in the figure below,

Figure 12(b): Storage facility for Low to Medium Level Waste

Nuclear Power Plants that have run out of space for spent fuel storage in their fuel pools have adopted several temporal and valid solutions while waiting for a final repository to be available. Some countries have opted for building interim centralized storage facilities while others store their spent fuel in specialised containers that are kept at the reactor site. An example of such specialised containers is shown in the figure below.

Figure 12(c): Interim Dry Storage facility for Spent fuel

Reprocessing

Spent fuel is about 96% uranium, 1% plutonium, and 3% fission products that are highly radioactive. In a reprocessing facility, the spent fuel is separated into its three components: uranium, plutonium and the waste that contains the fission products.

Reprocessing enables recycling of the uranium and plutonium into fresh fuel and produces a significantly reduced amount of waste (compared with treating all spent fuel as waste). Reprocessing facilities are usually located on sites that have many other processing and storage buildings located on the same site. These may include fuel storage ponds, plutonium processing facilities and stores, research and development facilities, and waste treatment plants.

Recycling

The uranium from reprocessing can be reused as fuel after further processing. The plutonium can be directly made into mixed uranium and plutonium oxide (MOX) fuel in which uranium and plutonium oxides are combined. In reactors that use MOX fuel, plutonium can substitute for the 235U found in normal uranium oxide fuel.

Waste

When most people talk about nuclear waste, they are referring to fuel that has been used in a reactor once. Most of the radioactivity associated with nuclear power remains contained in the fuel in which it was produced. This is why used fuel is classified as high-level radioactive waste. Nuclear plants also produce low-level radioactive waste which is safely contained and stored and then routinely disposed. Nuclear waste management is an important part of the fuel cycle. Wastes from the nuclear fuel cycle are categorised as high, medium or low level by the amount of radiation they emit. These wastes come from a number of sources. A brief discussion on each class of waste is given as follows,

1. Exempt Waste (EW)

Exempt waste contains such small concentrations of radionuclides that it does not require provisions for radiation protection, irrespective of whether the waste is disposed of in conventional landfills or recycled. Such material can be cleared from regulatory control and does not require any further consideration from a regulatory control perspective.

2. Very Short Lived Waste (VSLW)

Very short lived waste contains only radionuclides of very short half-life with activity concentrations above the clearance levels. Such waste can be stored until the activity has fallen beneath the levels for clearance, allowing for the cleared waste to be managed as conventional waste. Examples of very short lived waste are waste from sources using 192Ir and 99mTc and waste containing other radionuclides with short half-lives from industrial and medical 10 applications. These become exempt waste once they decay totally and are disposed as exempt waste.

3. Very Low Level Waste (VLLW)

Substantial amounts of waste arise from the operation and decommissioning of nuclear facilities with levels of activity concentration in the region of or slightly above the levels specified for the clearance of material from regulatory control. Other such waste, containing naturally occurring radionuclides, may originate from the mining or processing of ores and minerals. An adequate level of safety for VLLW may be achieved by its disposal in engineered surface landfill type facilities.

4. Low Level Waste (LLW)

This class of waste covers a very wide range of radioactive waste that has an activity content level just above that for VLLW. LLW contains low concentrations of long lived radionuclides and high concentrations of short lived radionuclides which may decay during the period of containment on site. Low level waste is waste that is suitable for near surface disposal (disposal at varying depths, typically from the surface down to 30 m). This class of waste is produced at all stages of the fuel cycle. In nuclear power plants, low-level waste includes items like gloves, tools or machine parts that have been exposed to radioactive materials and makes up most of the volume of waste produced by plants. Some low-level waste can be stored at the plant until it stops being radioactive and is safe to be disposed. Otherwise, low-level waste is collected and transported safely to disposal facilities.

5. Intermediate Level Waste (ILW)

Intermediate level waste is defined as waste that contains long lived radionuclides in quantities that need a greater degree of containment and isolation from the biosphere than is provided by near surface disposal. Disposal of ILW is done in a facility at a depth of between a few tens and a few hundreds of metres with both natural and engineered barriers. They are produced during reactor operation and during reprocessing.

6. High Level Waste (HLW)

High level waste is defined to be waste that contains such large concentrations of both short and long lived radionuclides that, compared to ILW, a greater degree of containment and isolation from the accessible environment is needed to ensure long term safety. Such containment and isolation is usually provided by the integrity and stability of deep geological disposal, with engineered barriers. HLW generates significant quantities of heat from radioactive decay, and normally continues to generate heat for several centuries. They are produced during reactor operation and during reprocessing and are mostly used fuel.

Disposal

Once removed from a reactor, used fuel assemblies initially are cooled down in a storage pool. The concrete and steel pool and the water shield workers from radioactivity. When cool enough that it no longer needs to be stored underwater, typically for 2 to 5 years after removal from the reactor, used fuel is transferred and stored in dry casks, which are large steel-reinforced concrete containers. These casks are designed for long term storage until a site is available for permanent disposal. They're safe enough to walk up to and touch.
At present, no disposal facilities (as opposed to storage facilities) are in operation in which spent fuel not destined for reprocessing, and the waste from reprocessing can be placed. A number of countries are carrying out studies to determine the optimum approach to the disposal of spent fuel and wastes from reprocessing. The general consensus favors its placement into deep geological repository.
The nuclear industry handles nuclear waste safely in compliance with the stringent requirements of the regulatory authority.

2.1.5 Radioactivity

The forces (attractive forces between unlike charges and repulsive forces between liked charges) within the atom work towards attaining a strong, stable balance by getting rid of excess energy known as nuclear or atomic energy.

Radioactivity is the decay or disintegration of an unstable nucleus to form one or more stable nuclei with the release of Energy and radiation. The nuclei of some isotopes that are naturally unstable and radioactive decompose spontaneously to release radiation. This process is called **Natural radioactivity**. Radioactivity can also be achieved by using man made methods to cause stable isotopes to become unstable with the subsequent release of radiation. This process is called **artificial** or **induced radioactivity**. Radiation from Natural radioactivity is indistinguishable from induced or artificial radioactivity.

Radiation is defined as energy given off by matter in the form of tiny fast-moving particles (e.g. Alpha particles, neutrons etc.) or pulsating electromagnetic waves (e.g. gamma rays). Radiation travels and spreads out as it goes. Not all radiation emanate from the nucleus of atoms. Radiation from the nucleus of an atom is known as nuclear radiation.

There are four major types of radiation: alpha, beta, neutrons, and electromagnetic waves such as gamma rays. They differ in mass, energy and how deeply they penetrate people and objects.

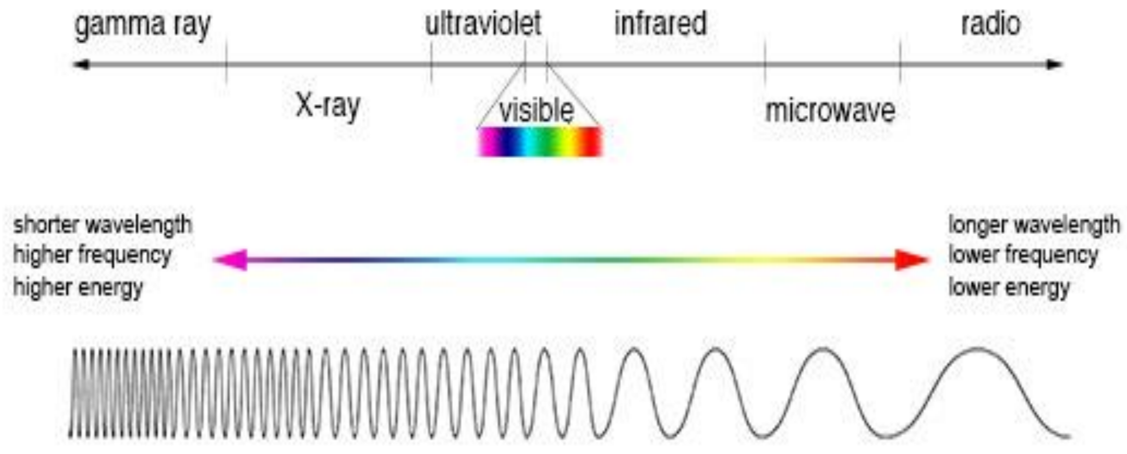
The first is an **alpha particle**. These particles consist of two protons and two neutrons and are the heaviest type of radiation particle. Many of the naturally occurring radioactive materials in the earth, like uranium and thorium, emit alpha particles. An example most people are familiar with is radon gas.

The second kind of radiation is a **beta particle**. It's an electron that is not attached to an atom. It has a small mass and a negative charge. Tritium, which is produced by cosmic radiation in the atmosphere and exists all around us, emits beta radiation. Carbon-14, used in carbon-dating of fossils and other artefacts, also emits beta particles.

The third is a **neutron** and this is a particle that doesn't have any charge and is present in the nucleus of an atom. Neutrons are commonly seen when uranium atoms split, in a nuclear reactor. It is the neutrons that sustain the nuclear reaction used to generate Nuclear power.

The last kind of radiation is **electromagnetic waves or radiation**. Electromagnetic waves can be described as a stream of very tiny particles, called **Photons**, each traveling in a wave-like pattern. Each photon contains a certain amount of energy and unlike the other kinds of radiation, photons have no mass or charge. Electromagnetic waves are probably the most familiar type of radiation because they have a wide range of uses. The visible light that comes from a lamp and the radio waves that come from radio stations are two types of electromagnetic radiation. The other types of electromagnetic radiation are microwaves, infrared rays, ultraviolet rays, X-rays and gamma rays. Electromagnetic waves can be classified in terms of energy, wavelength, or frequency. Energy is measured in electron volts (eV), Frequency in cycles per second, or Hertz (Hz) and Wavelength is measured in meters (m). Each of these three quantities for describing electromagnetic waves are related to each other in a precise mathematical way. The different types of electromagnetic radiation are defined by the amount of energy found in their photons. Radio waves have photons with low energies, microwave photons have a little more energy than radio waves, infrared photons have still more, then visible, ultraviolet, X-rays, and, the most energetic of all, gamma-rays. Although all electromagnetic waves travel at the speed of light in a vacuum, they do so at a wide range of frequencies, wavelengths, and photon energies.

The **electromagnetic spectrum** is the entire distribution of electromagnetic waves according to frequency , wavelength and photon energies. The spectrum covers electromagnetic waves with frequencies ranging from below 1 hertz to above 10^{25} hertz, corresponding to wavelengths from thousands of kilometres down to a fraction of the size of an atomic nucleus. This frequency range is divided into separate bands. There are no precise accepted boundaries between any of these bands and so the bands tend to overlap. Beginning at the low frequency (long wavelength) end of the spectrum these are, radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays at the high-frequency (short wavelength) end.



Comparison of wavelength, frequency and energy for the electromagnetic spectrum. The narrow range of visible light is shown enlarged at the bottom

The electromagnetic waves in each of these bands have different characteristics, such as how they are produced, how they interact with matter, and their practical applications.

Ionization is the process where sufficient energy is imparted to an atom to remove an orbiting electron from the electric field of the nucleus. This results in the production of a positively charged ion and a negatively charged displaced electron. Some radiations have sufficient energy to cause ionization in the material through which they pass, and hence are referred to as "ionizing radiations". Others do not have sufficient energy to carry out ionization and hence are referred to as "non-ionizing" radiations.

Ionizing Radiation refers to subatomic particles or electromagnetic waves that have sufficient energy to ionize atoms or molecules in matter by detaching electrons from them. It is the ionization process that results in the damaging effects of these radiations.

Gamma rays, X-rays and the higher ultraviolet part of the electromagnetic spectrum are ionizing radiation, whereas the lower energy ultraviolet, visible light, infrared, microwaves, and radio waves are non-ionizing radiation. The boundary between ionizing and non-ionizing radiation in the ultraviolet area is not sharply defined, since different molecules and atoms ionize at different energies, but is between 10 electronvolts (eV) and 33 eV.

Typical ionizing subatomic particles due to radioactive decay include alpha particles, beta particles and neutrons and almost all are energetic enough to be ionizing. Ionizing radiation is not detectable by human senses, so instruments such as Geiger counters must be used to detect and measure. However, very high intensities can produce visible light.
All types of nuclear radiation are also ionizing radiation, but not all types ionizing radiation are nuclear radiation. For example, x-rays are a type of ionizing radiation, but they are not nuclear radiation because they do not originate from atomic nuclei.

Direct ionizing radiation consists of charged particles. Such particles include energetic electrons (beta particles), protons, alpha particles, and heavy ions (ionized atoms). This type of ionizing radiation interacts with matter primarily through the Coulomb or electrostatic force, repelling or attracting electrons from atoms and molecules by virtue of their charges.

Indirect ionizing radiation consists of uncharged particles mostly photons above 10 keV (X rays and gamma rays) and all neutrons. X-ray and gamma-ray photons interact with matter and cause ionization in at least three different ways: photoelectric effect, Compton effect and pair production. During these processes intermediate charged particles such as photoelectrons and recoil protons are produced that actually cause the ionization. (See interaction of radiation with matter)

Radionuclides are unstable elements that disintegrate to emit ionizing radiation**.**
All radionuclides are uniquely identified by the type of radiation they emit, the energy of the radiation, and their half-life.

Activity, used as a measure of the amount of a radionuclide present, is expressed in a unit called the Becquerel (Bq): one Becquerel is one disintegration per second. The half-life is the time required for the activity of a radionuclide to decrease by decay to half of its initial value.

Half-life of a radioactive element is the time that it takes for one half of its atoms to disintegrate. This can range from a mere fraction of a second to millions of years (e.g. iodine-

131 has a half-life of 8 days while carbon-14, has a half-life of 5730 years). Carbon-14 is used for carbon dating of fossils and artefacts. Carbon-dating simply makes use of the fact that carbon-14 is radioactive and emits beta particles. If you measure the beta particles, it tells you how much carbon-14 is left in the fossil, which allows you to calculate how long ago the organism was alive knowing the half-life of carbon-14.

Nuclear fission is the splitting of a heavy nucleus into lighter ones (daughter nuclei) with the release of large amount energy in the form of heat and radiation.
For example if the nucleus of a heavy atom such as uranium is made to absorb a neutron by bombarding or irradiating it with neutrons, the nucleus can become unstable and split into smaller nuclei releasing large amount of heat. In the case of uranium, more neutrons (radiation) are produced. The neutrons produced go on to split more atoms starting a chain reaction which can be controlled. The chain reaction can produce very large amount of heat energy that can be used to convert large volumes of water into steam. The steam can be used to turn steam turbines to produce electricity. This is the principle of the nuclear power plant.
Typical fission events release about two hundred million eV (200 MeV) of energy. In contrast, most chemical oxidation reactions (such as burning coal) release at most a few eV per event. So, nuclear fuel such as uranium contains as at least ten million times more usable energy per unit mass than chemical fuel such as coal. Although nuclear fission can occur naturally, fission as encountered in the modern world is usually a deliberate man-made nuclear reaction.

Nuclear fusion is the merging of two light nuclei to form a single heavier nucleus with the release of energy. Energy is released because the mass of the resulting single nucleus is less than the total mass of the two original nuclei. The leftover mass becomes energy in accordance with Einstein's equation ($E=mc^2$), which says in part that mass and energy can be converted into each other. The sun, along with all other stars, is powered by nuclear fusion. If this can be replicated on earth, it could provide virtually limitless clean, safe and affordable energy to meet the world's energy demand. Research is ongoing in this regard and there is not successful application of nuclear fusion by man yet.

2.1.6 Sources of Radiation

Radiation is all around us and people are exposed to natural radiation sources (called background radiation), as well as human-made sources on a daily basis.

Natural radiation comes from many sources including more than 60 naturally-occurring radioactive materials found in soil, food, water and air. Radon, a naturally-occurring gas that is produced from the decay of naturally occurring uranium emanates from rocks and soils and is a source of natural radiation. Every day, people inhale and ingest radionuclides from air, food and water. People are also exposed to natural radiation from cosmic rays, particularly at high altitude. Cosmic rays interact with the Earth's atmosphere to produce secondary cosmic particles such as muons, mesons, and positrons. They may also produce radioisotopes on Earth (for example, carbon-14), which in turn decays and emits ionizing radiation. Cosmic rays and the decay of radioactive isotopes are the primary sources of natural ionizing radiation on Earth contributing to background radiation. On average, 80% of the annual dose of background radiation that a person receives is due to naturally occurring terrestrial and cosmic radiation sources. Background radiation levels vary geographically due to geological differences. Exposure in certain areas can be more than 200 times higher than the global average.

Human exposure to radiation also comes from human-made sources such as nuclear fission in nuclear power generation, nuclear weapon testing, medical uses of radiation for diagnosis or treatment, radioactive sources used in Industry and research. Today, the most common human-made sources of ionizing radiation are medical devices, including X-ray machines.

2.2 Nuclear Material and Technology Applications

A wide variety of uses have been known for nuclear materials as a result of radiations these materials emit. Radiation is used in household applications, medicine, academics, and industry. In addition, radiation has useful applications in such areas as agriculture, archaeology (carbon dating), Engineering, space exploration, geological exploration (including mining), electricity generation and many others.

Figure 13: Nuclear Technology Applications

2.2.1 Medical and other uses of nuclear materials.

A variety of nuclear materials and procedures are used to diagnose, monitor, and treat a wide range of metabolic processes and medical conditions in humans. Medical procedures using radiation have saved thousands of lives through the detection and treatment of conditions ranging from hyperthyroidism to bone cancer.

The radioactive materials used in medical applications are either by-product material (nuclear material produced in a reactor), accelerator produced nuclear material, or radiation-producing machines such as x-ray machines. Medical use of such materials falls broadly into two categories: diagnostic and therapeutic procedures.

Diagnostic procedures, such as those used in nuclear medicine, involve the use of relatively small amounts of radioactive materials to help image certain organs. Two examples of nuclear medicine procedures are the use of technetium-99 in the diagnosis of bone, heart or other organs and radioactive iodine in the imaging of the thyroid gland. The radioactive materials typically are injected into the patient; this allows physicians to locate and identify tumors, size anomalies, and other physiological and functional organ problems.

Therapeutic uses of radioactive materials include teletherapy, brachytherapy and therapeutic nuclear medicine. The purpose of all three is to kill cancerous tissue, reduce the size of a tumor, and/or reduce pain.

In teletherapy, an intense beam of radiation from a high-activity source external to the patient is focused on the tissue. An example of teletherapy is the use of a device called the Gamma Knife, which uses a collimating beam to focus radiation from numerous cobalt-60 sources to a specific location deep within the tissue.

In brachytherapy, one (or more) lower activity radioactive sources is placed close to, or within, cancerous tissue in the breast, prostate, cervix, etc. Brachytherapy sources include sealed "seeds" that are injected or surgically implanted and then removed after the prescribed dose has been received by the patient. Intravascular brachytherapy systems use small sources that are placed into arteries using catheters.

In therapeutic nuclear medicine, relatively high dosages of radioactive materials are injected into, or ingested by, the patient. A common example of this process is the use of radioactive iodine to destroy or shrink a diseased thyroid. In each case the materials remain radioactive for a relatively short period of time (short half-lives of decay).

Radioactive materials are an essential part of biomedical research into the causes and cures for diseases like AIDS, cancer and Alzheimer's. In the United States, at least 80% of all new drugs are tested with radioactive materials before the Food and Drug Administration can approve them as safe and effective.

Nuclear Technology plays a pivotal role in health delivery where its application is found in imaging, diagnosis & treatment of cancers and others as well as sterilization of medical equipment.

The most common of the medical procedures involve the use of X-rays, a type of radiation that can pass through human skin. When x-rayed, the bones and other structures cast shadows because they are denser than the skin, and those shadows can be detected on photographic film. The effect is similar to placing a pencil behind a piece of paper and holding the pencil and paper in front of a light. The shadow of the pencil is revealed because most light has enough energy to pass through the paper, but the denser pencil stops all the light The difference is that x-rays are invisible, so the need for a photographic film. This allows doctors and dentists to spot broken bones and dental problems.

X-rays and other forms of radiation also have a variety of therapeutic uses. They are used to kill cancerous tissues, reduce the size of a tumour, or reduce pain. For example, radioactive iodine (specifically iodine-131) is frequently used to treat thyroid cancer. X-ray machines have also been connected to computers in machines called computerized axial tomography (CAT) or computed tomography (CT) scanners. These instruments provide doctors with colour images that show the shapes and details of internal organs. This helps physicians locate and identify tumours, size anomalies, or other physiological or functional organ problems.

In some medical procedures, slightly radioactive substances are administered to patients. These substances which are attracted to certain internal organs such as the pancreas, kidney, thyroid, liver, or brain, are used to diagnose clinical conditions of these organs

2.2.2 Uses in Science and Agriculture

The agricultural industry makes use of radiation to improve food production and packaging. Plant seeds, for example, have been exposed to radiation to bring about new and better types of plants. Over 800 new varieties of hardier, more disease-resistant crops—including peanuts, tomatoes, onions, rice, soybeans and barley—have been developed in agricultural research laboratories through the use of radioactive materials.

Besides making plants stronger, radiation can be used to control insect populations, thereby decreasing the use of dangerous pesticides. Radioactive material is also used in gauges that measure the thickness of eggshells to screen out thin, breakable eggs before they are packaged in egg cartons. In addition, many of our foods are packaged in polyethylene shrink wrap that has been irradiated so that it can be heated above its usual melting point and wrapped around the foods to provide an airtight protective covering.
In Agriculture, nuclear technology is applied in mutation breeding, food preservation, insect & pest Control and Crop Protection and thereby ensuring food security.

2.2.3 Industrial Uses

Today, practically every industry uses radiation in some way. For example, radioactive materials are being used to:

1. Inspect metal parts and welds for defects
2. Measure, monitor and control the thickness of sheet metal, textiles, paper napkins, newspaper, plastics, photographic film and other products
3. Calibrate instruments
4. Manufacture ceramics and glassware
5. Generate heat and power for remote weather stations, space satellites and other special applications

Nuclear Technology is applied in the production of large quantities of reliable, affordable and clean energy that is safe for electricity generation. It is also used in making saltwater drinkable through desalination. Water desalination is the process of removing salt from saltwater to make the water drinkable. However, this process requires a lot of energy. Nuclear energy facilities can provide the large amount of energy that desalination plants need to provide fresh drinking water.

Foods, medical equipment, and other substances are exposed to certain types of radiation (such as x-rays and gamma rays) to kill germs without harming the substances that are being disinfected and also without making them radioactive. When treated in this manner, foods take much longer to spoil, and medical equipment (such as bandages, hypodermic syringes, and surgical instruments) are sterilized without being exposed to toxic chemicals or extreme heat.
Radiation is used to help remove toxic pollutants, such as exhaust gases from coal-fired power stations and industry. For example, electron beam radiation can remove dangerous sulphur dioxides and nitrogen oxides from the environment. Many of the fabrics used to make clothing have been irradiated (treated with radiation) before being exposed to a soil-releasing or wrinkle-resistant chemical. This treatment makes the chemicals bind to the fabric, to keep

clothing fresh and wrinkle-free. The fabrics however do not become radioactive. Similarly, non-stick cookware is treated with gamma rays to keep food from sticking to the metal surface. Reflective signs are treated with radioactive tritium and phosphorescent paint while ionizing smoke detectors make use of a tiny bit of radioactive americium-241. Gauges containing radioisotopes measure the amount of air whipped into ice cream, while others prevent spill over as soda bottles are carefully filled at the factory.

2.2.4 Engineering and Space Exploration

Nuclear Technology makes deep space exploration possible. The generators in unmanned spacecraft use the heat from plutonium to generate electricity and can operate unattended for years. This reliable long term source of electricity powers these spacecraft, even as they venture deep into space. Thus radioactive materials fuel space crafts and supply electricity to satellites that are sent on missions to the outermost regions of the solar system.

Engineers use gauges containing radioactive substances to measure the thickness of paper products, fluid levels in oil and chemical tanks, and the moisture and density of soils and material at construction sites. They also use an x-ray process, called radiography, to find imperceptible defects in metallic castings and welds. Radiography is also used to check the flow of oil in sealed engines and the rate and way that various materials wear out. Well-logging devices use a radioactive source and detection equipment to identify and record formations deep within a bore hole (or well) for oil, gas, mineral, groundwater, or geological exploration.

2.2.5 Archaeology

Archaeologists also use radioactive substances to determine the ages of fossils and other objects through a process called carbon dating. For example, in the upper levels of the atmosphere, cosmic rays strike nitrogen atoms and form a naturally radioactive isotope called carbon-14. Carbon is found in all living things, and a small percentage of it is carbon-14. When a plant or animal dies, it no longer takes in new carbon and the carbon-14 that it accumulated throughout its life begins the process of radioactive decay. As a result, after a few years, an old object has a lower percent of radioactivity than a newer object. By measuring this difference, archaeologists are able to determine the approximate age of objects.

2.2.6 Academic & Scientific Application

Universities, colleges and other academic and scientific institutions use nuclear materials in laboratory demonstrations, experimental research, and a variety of health physics applications. For example, just as doctors can label substances inside people's bodies, scientists can label substances that pass through plants, animals and various media. This allows researchers to study such things as the paths that different types of air and water pollution take through the environment. Similarly, radiation has helped scientists to learn more about the types of soil that different plants need to grow, the sizes of newly discovered oil fields, and the tracks of ocean currents. In addition, researchers use low-energy radioactive sources in gas chromatography to identify the components of petroleum products, smog and cigarette smoke, and even complex proteins and enzymes used in medical research.

2.2.7 Electricity Generation

Electricity produced by nuclear fission in a nuclear power plant is one of the greatest uses of radiation. Nuclear power plants produce large amounts of Clean, reliable, sustainable and affordable electricity.

2.2.8 Household Uses

The radio in our homes captures radio waves emitted by radio stations. Microwave radiation is produced by the Microwave oven for cooking and heating of food and is also used by astronomers to learn about the structure of nearby galaxies. Night vision goggles pick up the infrared light emitted by the skin and objects with heat. Remote controls use infrared radiation to communicate with various gadgets. In space, infrared light helps astronomers to map the dust between stars. The human eyes detect visible light. Fireflies, light bulbs, the sun, the moon and the stars all emit visible light. Ultraviolet light is used to disinfect drinking water in some homes.

2.3 Nuclear Reactor Components

There are several components common to most types of reactors. Few of these components are discussed in this session.

2.3.1 Fuel

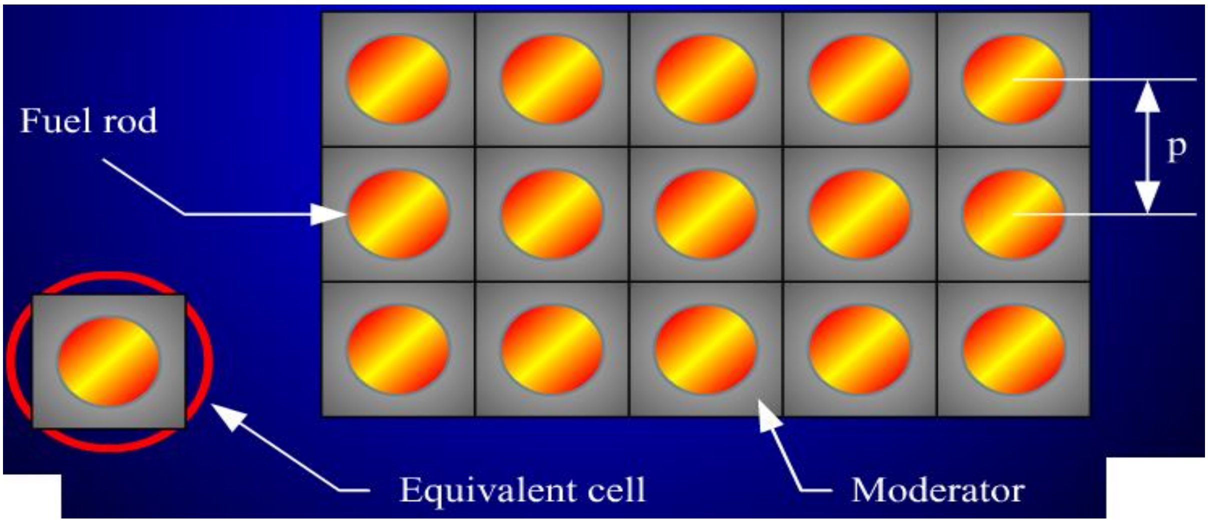
Uranium is the basic fuel. Usually pellets of uranium oxide (UO_2) are arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core. In a 1000 MWe class PWR there might be 51,000 fuel rods with over 18 million pellets.

In a new reactor with new fuel a neutron source is needed to get the reaction going. Usually this is beryllium mixed with polonium, radium or other alpha-emitter. Alpha particles from the decay cause a release of neutrons from the beryllium as it turns to carbon-12. Restarting a reactor with some used fuel may not require this, as there may be enough neutrons to achieve criticality when control rods are removed.

2.3.2 Moderator

Material in the core which slows down the neutrons released from fission so that they cause more fission in the reactor core. It is usually water, but may be heavy water or graphite.

The figure below shows the arrangement of fuel rods in a the core of a nuclear reactor in a square lattice, and indicating the pitch (P) and the moderator.



2.3.3 Control Rods

These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it. In some PWR reactors, special control rods are used to enable the core to sustain a low level of power efficiently. (Secondary control systems involve other neutron absorbers, usually boron in the coolant – its concentration can be adjusted over time as the fuel burns up.) PWR control rods are inserted from the top, BWR cruciform blades from the bottom of the core.

In fission, most of the neutrons are released promptly, but some are delayed. These are crucial in enabling a chain reacting system (or reactor) to be controllable and to be able to be held precisely critical.

2.3.4 Coolant
A fluid circulating through the core so as to transfer the heat from it. In light water reactors the water moderator functions also as primary coolant. Except in BWRs, there is secondary coolant circuit where the water becomes steam. A PWR has two to four primary coolant loops with pumps, driven either by steam or electricity.

2.3.5 Pressure Vessel or Pressure Tubes
Usually a robust steel vessel containing the reactor core and moderator/coolant, but it may be a series of tubes holding the fuel and conveying the coolant through the surrounding moderator.

2.3.6 Steam Generator
Part of the cooling system of pressurised water reactors (PWR & PHWR) where the high-pressure primary coolant bringing heat from the reactor is used to make steam for the turbine, in a secondary circuit. Essentially a heat exchanger like a motor car radiator. Reactors have up to six 'loops', each with a steam generator. Since 1980 over 110 PWR reactors have had their steam generators replaced after 20-30 years' service, 57 of these in USA.

* These are large heat exchangers for transferring heat from one fluid to another – here from high-pressure primary circuit in PWR to secondary circuit where water turns to steam. Each structure weighs up to 800 tonnes and contains from 300 to 16,000 tubes about 2 cm diameter for the primary coolant, which is radioactive due to nitrogen-16 (N-16, formed by neutron bombardment of oxygen, with half-life of 7 seconds). The secondary water must flow through the support structures for the tubes. The whole thing needs to be designed so that the tubes don't vibrate and fret, operated so that deposits do not build up to impede the flow, and maintained chemically to avoid corrosion. Tubes which fail and leak are plugged, and surplus capacity is designed to allow for this. Leaks can be detected by monitoring N-16 levels in the steam as it leaves the steam generator.

2.3.7 Containment
The structure around the reactor and associated steam generators which is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any serious malfunction inside. It is typically a metre-thick concrete and steel structure.

Newer Russian and some other reactors install core melt localisation devices or 'core catchers' under the pressure vessel to catch any melted core material in the event of a major accident

2.4 Basic Atomic Physics

2.4.1 Basic Atomic Structure

All matter consists of tiny particles called atoms. Atoms contain three sub-atomic particles called protons, neutrons and electrons. The protons and neutrons are found in the nucleus at the centre of the atom while the electrons are arranged in shells or energy levels around the nucleus. The nucleus forms a very small part of the atom but it is the heaviest part of the atom and gives the atom its mass. The table below shows the properties of these three sub-atomic particles.

Particle	Relative mass	Relative charge
Proton	1	+1
Neutron	1	0
Electron	Almost zero	–1

Because the protons are positively charged and the neutrons are neutral (carry no charge), the nucleus is said to have a net positive charge often referred to as Nuclear charge. The number of electrons (negatively charged particles) in an atom is always the same as the number of protons, so atoms are electrically neutral overall. Atoms can lose or gain electrons and when they do, they form charged particles called ions. If an atom loses one or more electrons, it becomes a positively charged ion (cation) and if an atom gains one or more electrons, it becomes a negatively charged ion (anion).

The composition of the nucleus of an atom as well as the electrons determine which element the atom represents. An **element** is a pure substance that is made up of atoms of the same kind with the same number of protons and electrons. Hydrogen (H), Carbon (C), Nitrogen (N), Oxygen (O), Copper (Cu), Zinc (Zn), Gold (Au), Aluminium (Al), Silver (Ag), lead (Pb), Uranium (U) and Thorium (Th), are some examples of naturally occurring elements.

Copper and Gold for example are different elements because the number of protons, neutrons and electrons in their atoms are different. Atoms of different elements combine in chemical reactions using their electrons to form compounds. Electrons therefore determine the chemical properties of elements. Everything on the surface of the earth, living and non-living are actually made of elements, compounds, mixtures etc. resulting from different combinations both physical and chemical. Therefore the structure and make up of everything can be traced to the Atom.

The number of protons in the nucleus of an atom is referred to as the **Atomic number (Z)**. In an electrically neutral atom, the atomic number is also equal to the number of electrons.

Z = p or Z = e (for an electrically neutral Atom)

The total number of the protons and neutrons in the nucleus of an atom is referred to as the **mass number (A)**.

A = p + n or   A = Z + n

An element X with atomic number Z and Mass number A is represented as $^{A}_{Z}\mathbf{X}$

- All atoms of the same element have the same atomic number (Z) and have the same number of protons. For example the element oxygen has atomic number 8 and therefore all atoms of oxygen have 8 protons.
- Atoms of different Elements have different atomic numbers and therefore different number of protons. Hydrogen has atomic number 1 and has 1 proton as against 7 for

Nitrogen, 8 for oxygen, 79 for Gold and 92 for Uranium. No two different elements can have the same atomic number.

- There exists, atoms of the same elements with the same atomic number (same number of protons) but different mass numbers resulting from differences in the number of neutrons. This phenomenon is called **Isotopy** and **Isotopes** are atoms of the same element with the same atomic number but different mass numbers.

Some elements exhibit Isotopy and others don't. For example Carbon with atomic number 6 has three naturally occurring isotopes, carbon-12, carbon-13, and carbon-14. All three have 6 protons, but their neutron numbers are 6, 7, and 8, respectively. This means that all three isotopes have different mass numbers (carbon-14 being the heaviest), but share the same atomic number (Z=6).

Chemically, all three are indistinguishable, because the number of electrons in each of these three isotopes is the same.

Therefore isotopes of the same element are chemically identical. However some isotopes have the ability to circumvent this rule by transforming into another element entirely. This transformative ability is due do the fact that not all isotopes are stable. Some isotopes such as carbon-12 - will naturally continue to exist as carbon unless something extraordinary happens. Others like carbon-14, will at some point decay into a stable isotope. In this case, one of the neutrons in carbon-14 changes into a proton in a process called beta decay. This increases the number of protons from 6 to 7 and decreases the number of neutrons from 8 to 7 with the mass number maintained at 14. By so doing carbon-14 gets transformed into nitrogen-14 which has 7 protons and 7 neutrons. During this process, the nucleus of carbon-14 gets rid of excess energy (nuclear energy) in the form of radiation. The process is an example of radioactivity and carbon-14 is said to be radioactive.

2.4.2 Radioactive Decay and Nuclear Transformation Reactions

There are about 15 naturally occurring radioactive nuclides and more than 1600 man-made radioactive nuclides. Nuclides are atom species of two or more elements or atom species in general. They differ from isotopes which are atom species of a particular element. All radioactive nuclides are unstable and tend to undergo a transformation (or decay) to a stable nuclide. The transition from radioactive nuclide to stable nuclide may be a single step process, or it may involve one or more intermediate radioactive nuclides.

Radioactive decay happens randomly in individual atoms of an unstable nuclide. However, across all atoms of any given quantity of a radioactive nuclide, the rate of decay can be characterised by the nuclide's half-life. The half-life is the period of time it takes one half of any given quantity of a radioactive nuclide to decay to one or more daughter products. Half-life periods range from less than one second to more than a trillion years. The half-life of some naturally occurring radioactive nuclides are shown in table……

Nuclide	**Symbol**	**Weight % Natural Isotopic Abundance**	**Half-Life**
Potasium-40	$_{19}K^{40}$	0.0120	1.277×10^{9} yrs
Rubidium-87	$_{37}Rb^{87}$	28.30	4.75×10^{10} yrs
Platinum-190	$_{78}Pt^{190}$	0.014	6.5×10^{11} yrs
Thorium-232	$_{90}Th^{232}$	100	1.39×10^{10} yrs
Uranium-235	$_{92}U^{235}$	0.711	7.038×10^{8} yrs

There are eight different ways that unstable nuclides undergo transformation to a daughter nuclide. The four most common are, ALPHA Emission, BETA Emission, Electron Capture and Positron Emission. The others are, Isomeric Transition, Neutron Emission, Gamma Emission and Internal Conversion.

In addition to the eight decay modes, there is another type of nuclide transformation known as Spontaneous Fission that happens in certain high mass number nuclides. It is different from the eight modes of decay in that, two daughter nuclides, instead of one result from the transformation. The daughters can have atomic numbers ranging from 27 to 62 and have mass numbers from 65 to 160. In addition to the two daughter nuclides, one to four neutrons are emitted for each spontaneous fission event. Spontaneous fission is usually a secondary mechanism in that, most nuclide that undergo spontaneous fission also decay at a much faster rate by either alpha or beta emission. Spontaneous fission half-lives are typically greater than 1×10^{15} yrs. Uranium-235 has a spontaneous fission half-life of 1.9×10^{17} years compared to its alpha decay half-life of 7.038×10^{8} years.

The atoms of most nuclides of high atomic mass numbers can also undergo fission when bombarded by a free neutron. In most cases, the neutron must have very high energy at the point of hitting the heavy nuclide before fission can occur. A collision between a neutron and a heavy nuclide does not mean fission will automatically occur. The probability for fission to occur upon a neutron-atom collision is not only dependent on the neutron's energy but also on the particular nuclide species involved. However, atoms of few nuclides have a fairly high probability of fissioning when struck by a neutron of very low energy. This situation is particularly important because neutrons emitted as a result of spontaneous fission or induced fission rapidly lose their initial high energy through non-capture and non-fission collision.

If a nuclide undergoes spontaneous fission and its atoms are easily fissioned by low energy neutrons, such a nuclide can sustain a fissioning chain reaction under certain condition of sufficient mass and physical configuration. Such nuclides are described as fissile. For all practical purposes, uranium-235 is the only naturally occurring fissile nuclide. Uranium-233 and Plutonium-239 are the two most plentiful man-made fissile nuclide.

All radioactive nuclides with an atomic number greater than 83 decay to a stable isotope of either lead (Pb) or bismuth (Bi) but in almost all cases, it is lead. The decay scheme for naturally occurring uranium-238 is shown below.

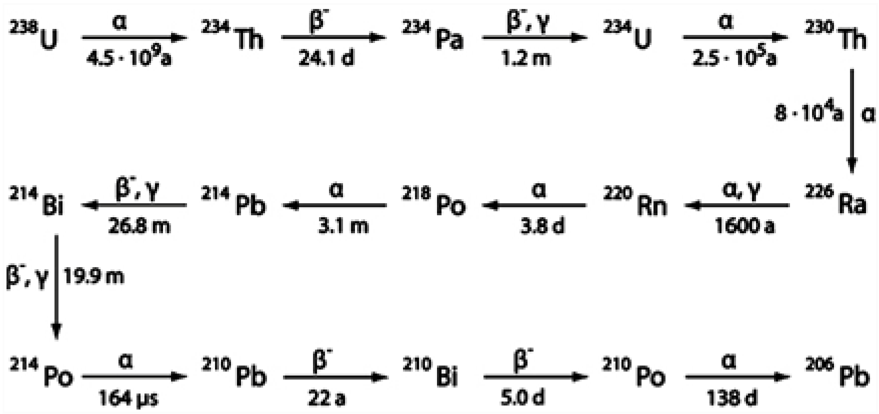


Figure 14: Decay Chain for U-238

Note that, “a” is years, “d” is days and “m” is minutes

2.4.1.1 BETA DECAY

During beta decay or beta emission, a neutron within the atom’s nucleus is transformed into a proton plus an electron. The proton remains within the nucleus while the electron is ejected from the nucleus. Thus for beta decay, the resulting daughter nuclide has an atomic number (ie proton number) which is one (1) greater than that of the parent nuclide while the mass number (number of protons and neutrons) remains the same as that of its parent.

2.4.1.2 ALPHA DECAY

An alpha particle that is emitted from a nucleus during alpha decay is identical to the nucleus of a helium atom which consist of two protons and two neutrons. The resulting daughter nuclide from an alpha emission has a mass that is four (4) less than its parent and an atomic number that is two (2) less than that of its parent nuclide.

2.4.1.3 ELECTRON CAPTURE

In electron capture decay, an orbital electron of the atom is captured by a proton within the nucleus, thus changing the proton to a neutron. The daughter nuclide of an electron capture event therefore has an atomic number of one (1) less than its parent, while the mass number remains the same.

2.4.1.4 POSITRON DECAY

Positron decay can be regarded as the emission of a positron from a proton within the nucleus, thus changing the proton to a neutron. The mass of a positron is about the same as that of an electron, thus positron emission results in a daughter nuclide with an atomic number of one (1) less than its parent and a mass number that is the same as that of the parent.

2.4.3 The Nuclear Chain Reaction

2.4.3.1 NUCLEAR FISSION

When the nucleus of an atom of high atomic mass fissions, the products of the splitting nucleus are two smaller (lighter) nuclei and one to four neutrons. A nucleus can fission either spontaneously or as a result of absorbing a sub-atomic particle. The absorption of a sub-atomic particle results in the formation of a different and highly excited nucleus. The products of the fission event has a total mass that is slightly less than the mass of the parent fissioning nucleus. The loss in mass is as a result of mass being converted into energy. Although the mass loss is very small, the energy released is very large.

Each time a fission neutron strikes a nuclide within its environment, there are three (3) possible results;

1. The neutron merely bounces off the struck nuclide given up some of its energy to the nuclide
2. The neutron may be captured by the struck nuclide in a non-fission reaction
3. The neutron may cause the struck nuclide to fission

The probability that any of these events will occur depends on the energy of the neutron and also the type of nuclide involved in the collision.

The energy of prompt fission neutrons cover a wide range from 10 million electron volts (MeV) down to thermal values of 0.025 electron volts. But majority of fission neutrons have initial energies of about 1 to 2 MeV. To sustain a chain reaction within the core of a nuclear reactor, fission neutrons need be slowed down (ie. thermalized) from their initial high energies of 1 to 2 MeV. The thermalization (slowing down) of neutrons is done by using a moderator material such as water or graphite. A moderator is any material whose nuclides have a very low neutron capture possibility and thus can be involved in many collisions with neutrons without neutron capture occurring.

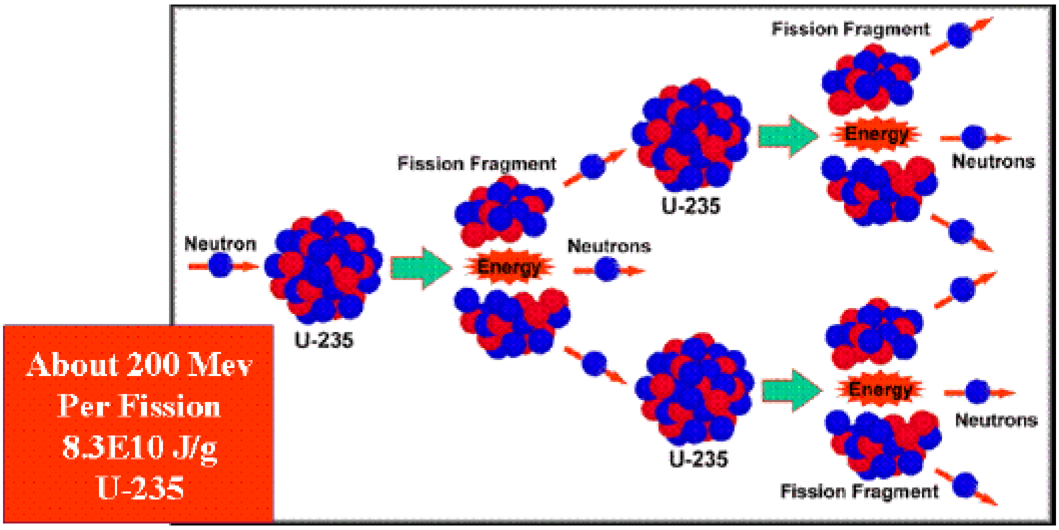


Figure 15: Fission Chain Reaction

2.4.3.2 NUCLEAR FUSION

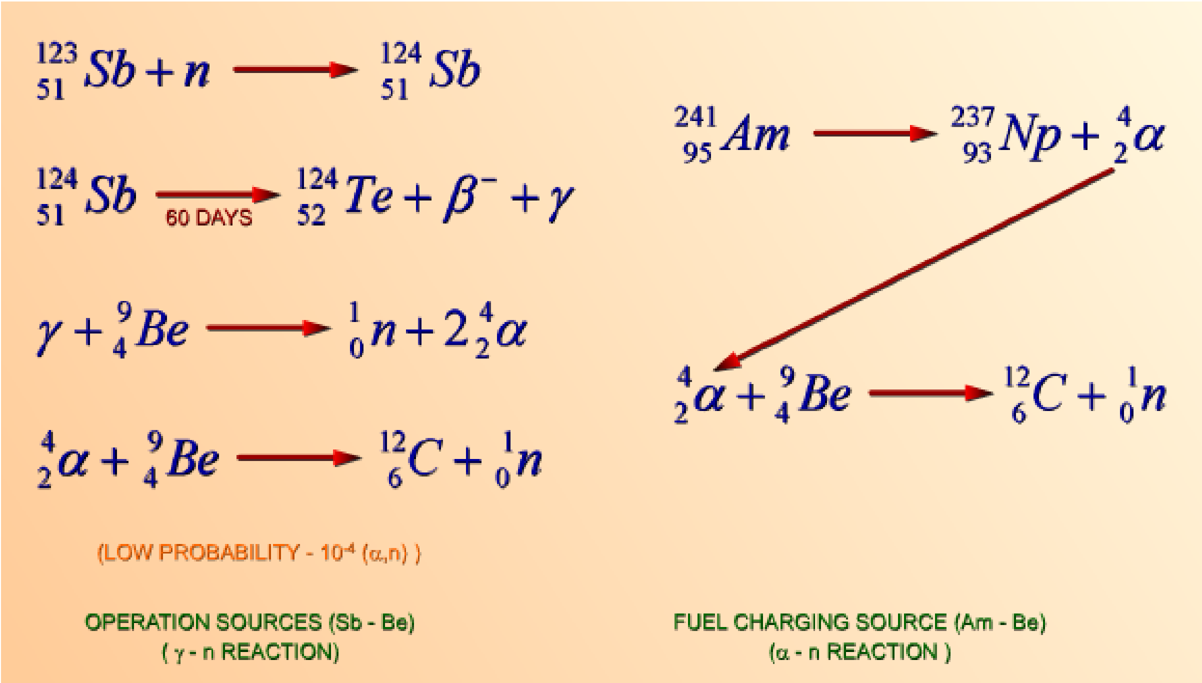
Thermonuclear fusion is the nuclear reaction that powers the stars throughout the universe, including the sun. In nuclear fusion, atoms of very light elements such as hydrogen are compressed under very high pressure and temperature and fused together to form atoms of slightly heavier elements, such as helium. In the process, some of the mass of the initial atom of light elements is converted to energy. The energy yield for this fusion process is higher than that for fission.

Fusion has the appeal of being a safe and environmentally sound energy source. However it needs a lot of investment in research and experimentation before commercial fusion electricity stations become a reality. However fission reactors for commercial production of electricity is a reality and produces base load electricity in many countries.

2.4.3.3 REACTOR START-UP AND EVOLUTION FROM SHUTDOWN

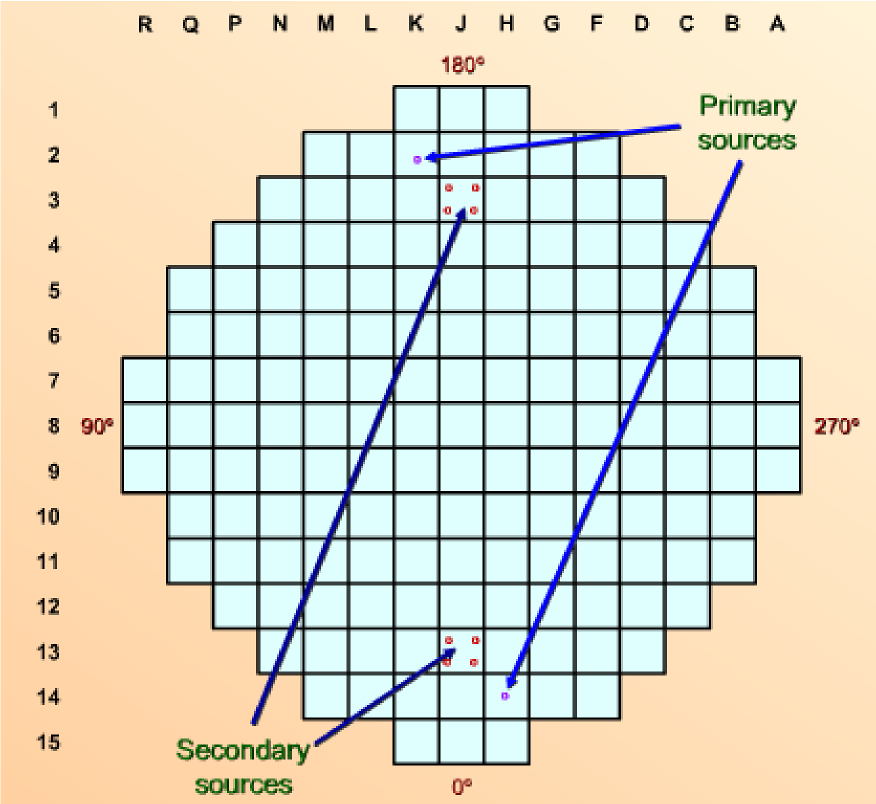
Neutrons are needed to start the operation of a new nuclear reactor or to let the reactor start operating after it has been shut down for maintenance. These neutrons must be produced from a critical mass of nuclear fuel. Critical mass of fuel is the amount of fuel which is needed to sustain a fission chain reaction in the core of a nuclear reactor. Photo neutrons are needed to start the operation of fresh reactor core. Photo neutrons sources are materials that emit neutrons from their nucleus when the nucleus becomes excited to a higher energy level than the binding energy value of the last neutron. The excitation of the nucleus results from the absorption of a photon energy (ie. gamma photon) by the nucleus.

In Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs), Antimony-Beryllium source is used to generate the photo neutrons which could be used for (1) starting up the reactor at beginning of life (BOL) of the plant or (2) starting the operation of the plant after shutdown. The Photo neutron generator is shown by the reaction,



The set of reactions above show the charging and operating mechanisms for the creation of neutrons needed to start the reactor. Primary neutrons are produced during charging through the fuel charging source (Am – Be). The Primary neutrons produced are then used to initiate the creation of neutrons at the operation side. The starting stable antimony isotope absorb these primary neutrons to become radioactive and emit a gamma photon during reactor operation. The gamma photon produced is then absorbed by Beryllium and this results in the production of secondary neutrons.

In the core of the reactor, both the primary neutron sources (Am –Be) and the secondary neutrons sources (Sn –Be) are strategically positioned to enhance the probability of these reactions occurring and their subsequent result in starting the reactor. The figure below shows the location of these sources in two fuel assemblies in the reactor core.



It is important to also note that, there are two main types of neutrons sources in the start-up and operation of nuclear reactors. These are, (1) Intrinsic and (2) External neutron sources. Intrinsic neutron sources are composed of the very reactor core materials. Delay neutrons and neutrons generated by spontaneous fission are included in this category.

External sources are materials that are intentionally placed in the core of the reactor to produce neutrons. They are needed in the reactor core because the intrinsic sources of neutron production have low activity and hence will not be able to produce the neutron levels needed for proper detection by the reactor instrumentation. External neutrons sources are therefore crucial.

2.4.4 Interaction of Neutron with Matter

The reactions between neutrons and nuclei are distributed into two main groups, namely scattering and absorption. In scattering reactions, the final result is simply an energy exchange between the two particles involved. Consequently the incident neutron remain free after interaction.

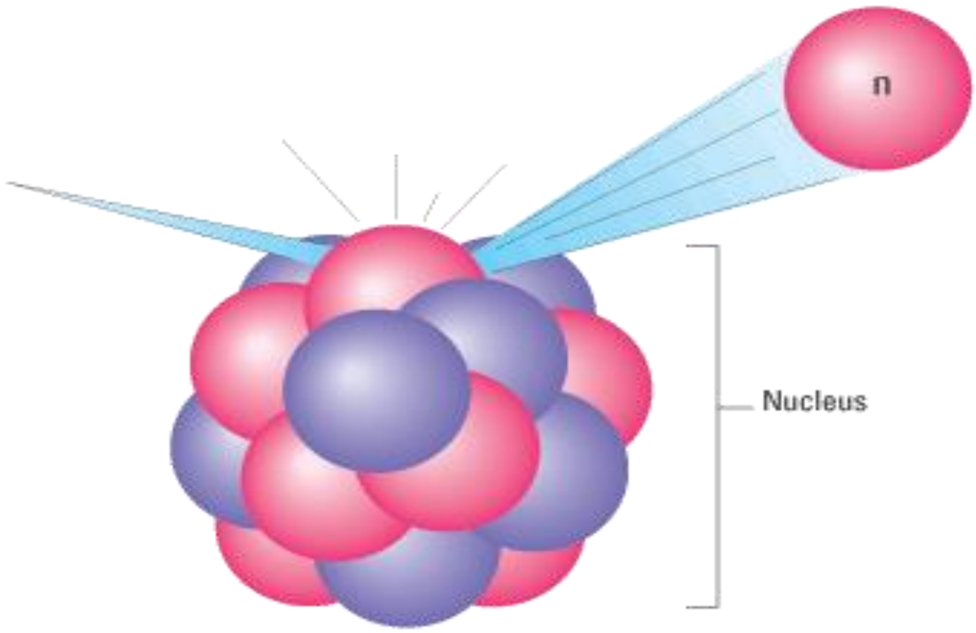
By contrast, in the absorption processes, the neutron is captured by the nucleus resulting in the formation of new particles. In the standpoint of nuclear reactors, the most important absorption reactions are radiative capture and fission.

Considering absorption and scattering as the main classification criteria, it is usual to classify neutron- nucleus reactions according to their products as follows,

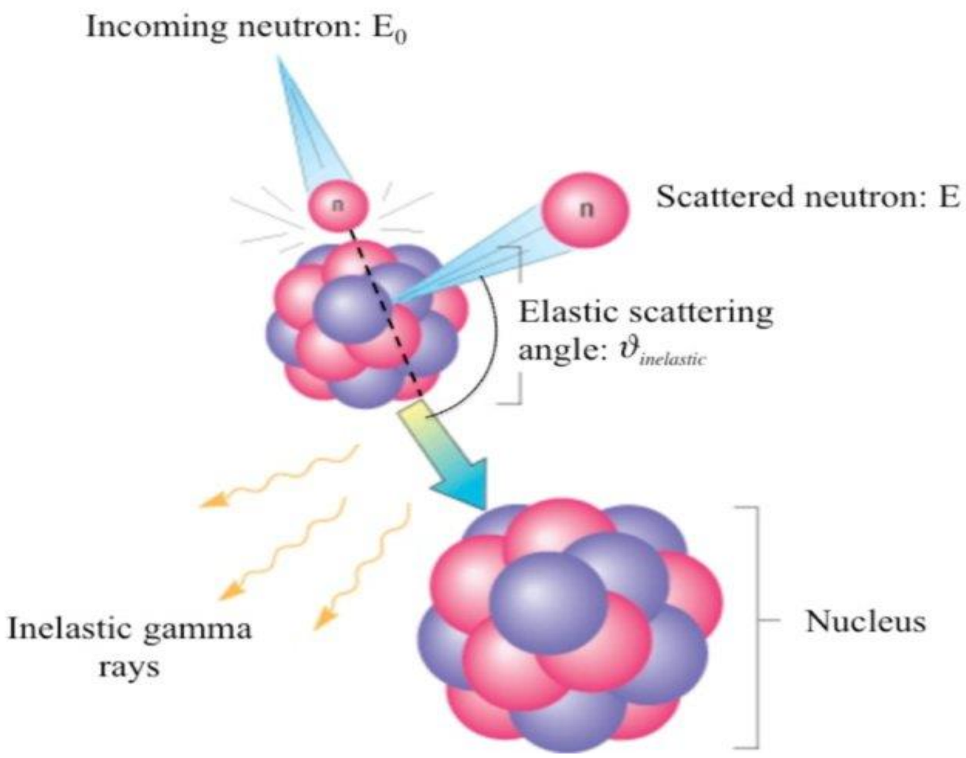
1. Elastic Scattering
2. Inelastic Scattering

3. Radiative Capture
4. Emission of Charged Particles
5. Reactions Producing Neutrons
6. Nuclear Fission

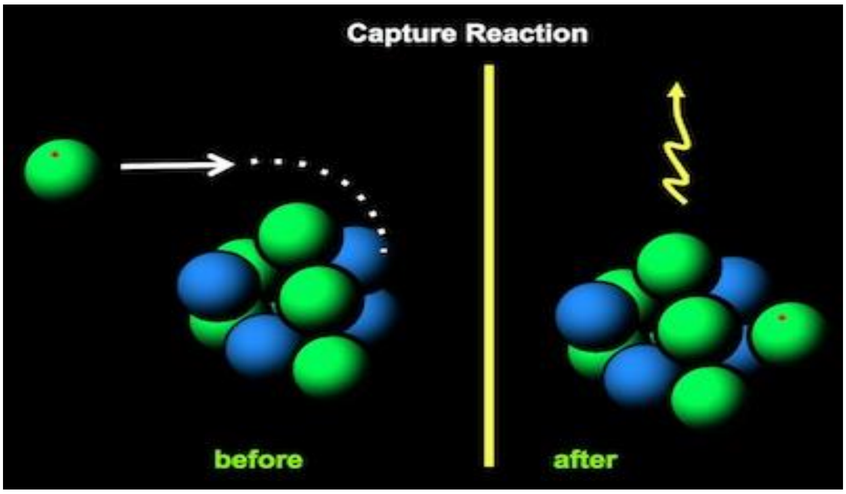
In elastic scattering, the reaction products are the same as those that were initially present, ie. the neutron and the target nucleus. It is a simple elastic collision between neutron and nucleus with no resulting photon emission because they initial nucleus participants in the reaction is always in the ground state even after the collision. This reaction is very important because, aside from radiative capture, it is the only interaction that occurs at any neutron energy and secondly, the reaction plays a major role in the moderation of fast neutrons.



Inelastic collision occurs when a nucleus captures a neutron that is later reemitted whether it be the same neutron it captured or another, while the nucleus is left in an excited state. The nucleus later returns to its ground state with the emission of gamma photon.



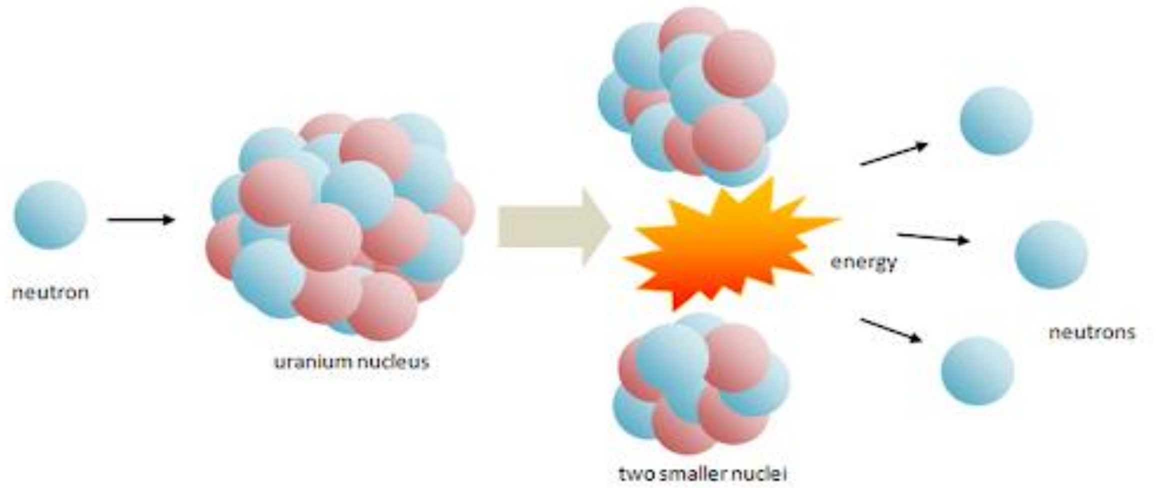
In radiative capture, the neutron is absorbed by the target nucleus, forming a new isotope heavier than the original nucleus, and one or more gamma rays are emitted. This reaction is also known as absorption. No neutrons are emitted in the process. This reaction plays very important role in reactor control where the need to control the population of neutrons in the core becomes paramount.



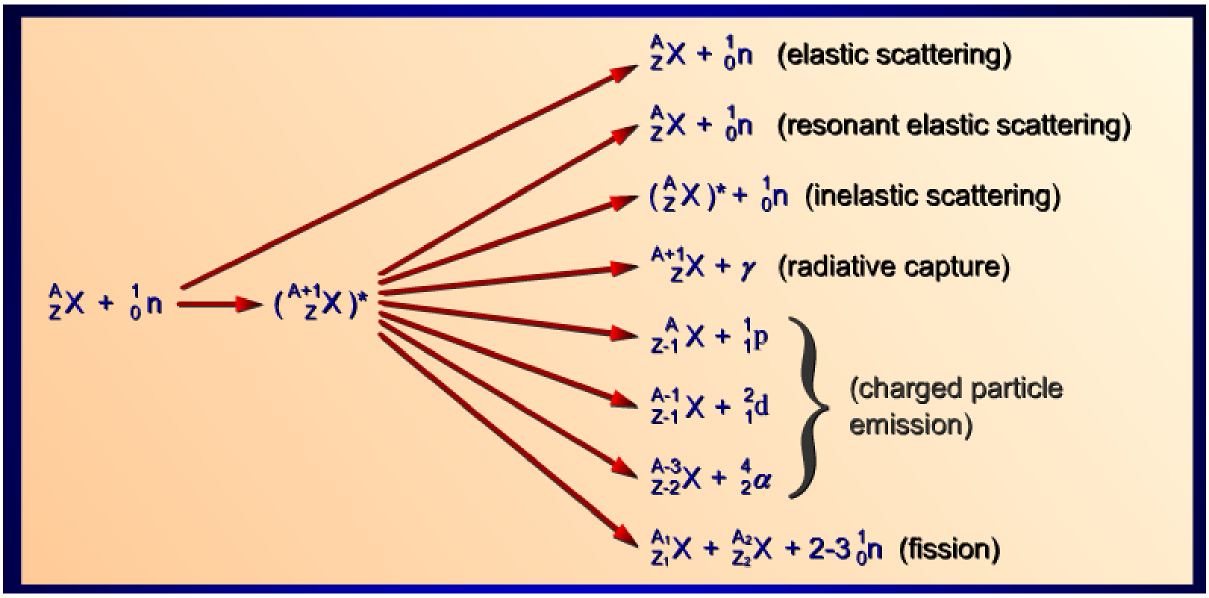
The emission of charged particles is a process that occurs when the reaction caused by a neutron gives as a result a nucleus that is different from the initial one and an electrically charged particle is emitted. This is also a process of absorption.

Neutron producing reactions are reactions that emit neutron after the capture of another particle or reactions in which a neutron is captured and as a result, two or more neutrons are emitted. These reactions are important since they serve as neutrons sources in nuclear reactors.

Nuclear fission occurs when a heavy nucleus absorbs a neutron and as a result it is split into two lighter nuclei called fragments or fission products, simultaneously two or more neutrons are also emitted.



A summary of the different neutron-nucleus reactions types are shown in the diagram below.



During fission, approximately 200 MeV of energy are released. It is however important to distinguish between the energy released in the process and the energy that can be used in the reactor with the aim of producing heat ie. Recoverable energy. Released and recoverable energy for the fission of uranium – 235 in MeV are shown in the table below.

Way		Released energy	Recoverable energy
Fission fragments		165	165
Decay of fission products	β rays	7	7
	γ rays	7	7
Neutrinos		12	-
Prompt γ photons		7	7
Neutrons		5	5
Capture γ photons		-	8-12
TOTAL		203	194-203

The products of all the neutron nucleus reactions are not the same and are characterized by their cross sections. Cross sections measure the probability of any one of occurrence of any one of the neutron-nucleus reactions. Neutrons are very important to the start-up and continuous operation of a nuclear reactor and hence their destruction or absorption through any neutron-nucleus interaction is not recommended. Absorption of neutrons only becomes relevant during reactor control and reactor shutdown.

The relative balance between the probabilities that a neutron is produced through a fission reaction to that of a neutron is absorbed through radiative capture reaction is a critical measure in nuclear application. The fission- capture relationship is expressed by using the cross sections of these reactions as,

$$\alpha \equiv \frac{\sigma_\gamma}{\sigma_f} \equiv \frac{probability\ \ that\ \ a\ \ neutron\ \ is\ \ destroyed\ \ or\ \ absorbed\left(radiative\ \ capture\right)}{probability\ \ that\ \ a\ \ neutron\ \ is\ \ produced\left(fission\right)}$$

The figure below shows the radiative capture and fission cross sections of some nuclei of Uranium and Plutonium.

Nucleus	σ_γ	σ_f	α	η	v
^{233}U	47.7	531.1	0.0899	2.287	2.492
^{235}U	98.6	582.2	0.169	2.068	2.418
^{239}Pu	268.8	742.5	0.362	2.108	2.871
^{241}Pu	368.0	1009.0	0.365	2.145	2.927

For example when uranium-235 involves in a reaction with a thermal neutron of energy 0.0253 electron volts, the probability that the neutron will get destroyed through absorption or radiative capture is 98.6 b and the probability that the interaction will result in the formation of new neutrons through fission is 582.2 b. It therefore imply that

$$\alpha \equiv \frac{98.6}{582.2} = 0.1694$$
$$\alpha^{-1} \equiv 5.90$$

The result shows that, fission occurrence probability is 5.9 times greater than the probability of radiative capture.

The average number of neutrons produced per fission per neutron absorbed by a fissile nucleus is known as the reproductive factor and is given as,

$$\eta \equiv \nu \frac{1}{1+\alpha}$$

where ν is the average number of neutrons produced by nuclear fission

In the case of uranium-235 discussed above,

$$\eta \equiv 2.418 \frac{1}{1+0.169} = 2.068$$

When uranium-235 absorbs a thermal neutron, uranium-236 nucleus is formed. The nucleus of uranium-236 that is formed has an excitation energy of 6.4 Mega electron volt (MeV) as shown in the table below with a critical energy of 5.20 MeV. Thus the nucleus will undergo fission. The nuclei that can split up by absorbing low energy neutrons (thermal neutrons) are called fissile nuclei.

Nucleus	Critical energy	Binding energy of the last neutron
^{232}Th	5.90	*
^{233}Th	6.50	5.1
^{233}U	5.50	*
^{234}U	4.60	6.6
^{235}U	5.75	*
^{236}U	5.20	6.4
^{238}U	5.85	*
^{239}U	5.50	4.9
^{239}Pu	5.50	*
^{240}Pu	4.00	6.4

On the other hand, if a nucleus of uranium- 238 absorbs a thermal neutron, a nucleus of uranium-239 will be formed with excitation energy of 4.9 MeV and critical energy of 5.5 MeV. In this instance, the thermal neutron is unable to provide the required energy and thus the nucleus will not split. However if the absorbed neutron has a kinetic energy greater than 0.6

MeV, the uranium-239 nucleus can be formed with an excitation energy that is equal to or greater than 5.5 MeV and therefore fission may occur.

Nuclei like that of uranium 238 which only fission with high energy neutrons (fast neutrons) are called fissionable nuclei but are still non-fissile.

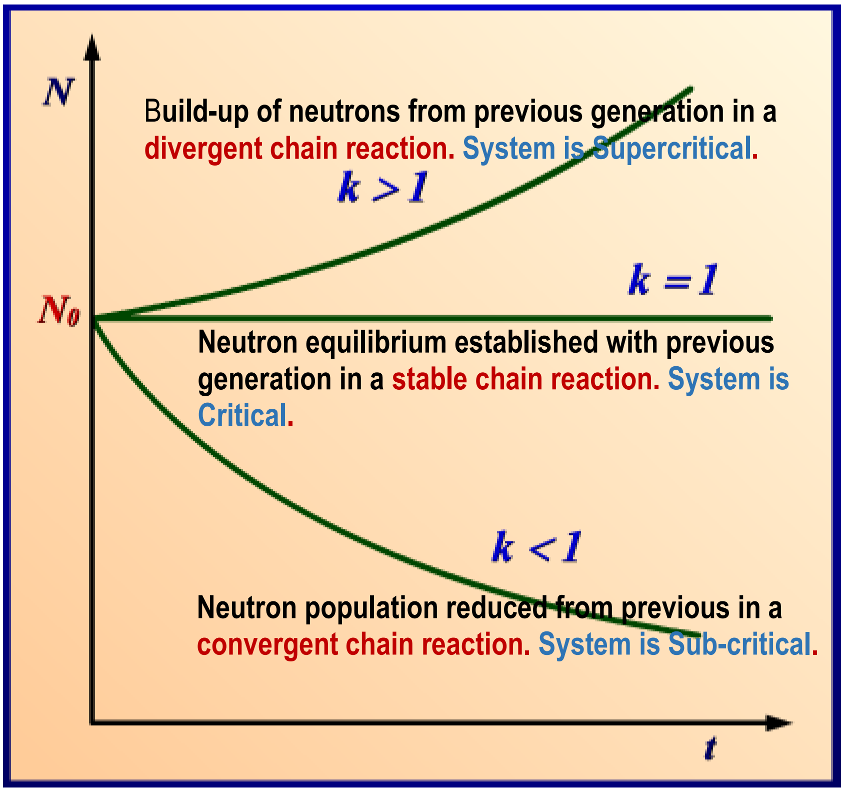
The vast majority of neutrons that are released in fission (usually more than 99 %) are emitted at the very same moment that the fission happens. These are called prompt neutrons.

Delayed neutrons are neutrons released by the fission fragments that are products of the fission reaction at the end of a relatively long period of time after fission occurs. Thus for all the neutrons released from fission, a part is instantly emitted providing the prompt neutrons while another part is emitted later constituting the delayed neutrons.

2.4.5 Concept of Reactor Criticality

Two phenomena of great importance occur during nuclear fission. First, the release of a tremendous amount of energy and, secondly the production of new neutrons. The combination of these two factors makes the construction of a nuclear reactor possible in which the fission chain reaction can self-maintained providing at the same time a continuous amount of energy. The chain reaction is represented by a factor known as the Multiplication Factor which is defined as the ratio between the number of fissions or neutrons of a given generation and the number of fissions or neutrons of the previous generation.

Depending on the value of the Multiplication Factor, three (3) different situations can result. These situations are illustrated in the figure below showing the temporal evolution of neutron population in a nuclear reactor according to its effective multiplication factor.



If the multiplication factor is greater than 1, the neutron population will grow from one generation to the other generation. In this situation, the chain reaction is said to be divergent since the number of fission grows over time and the amount of energy released also increases accordingly and the reactor system is said to be supercritical.

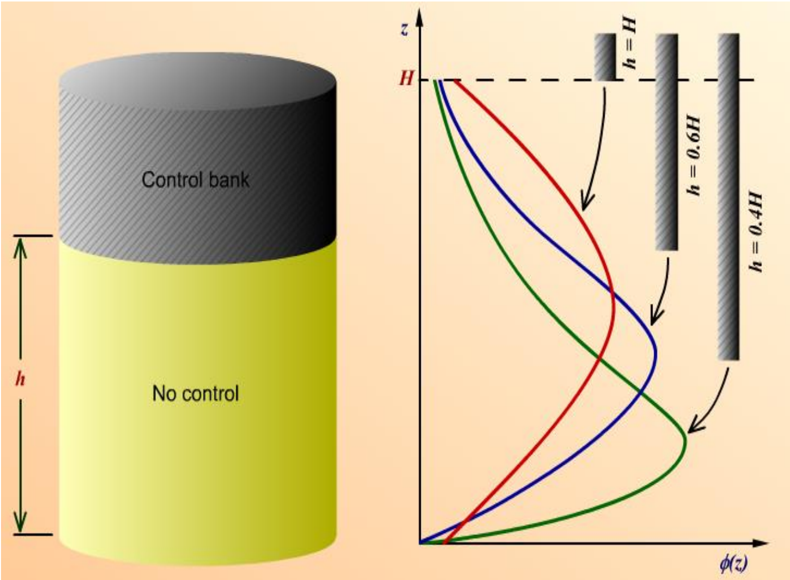
If the multiplication factor is exactly equal to 1, the number of fissions or neutrons remains constant over time making the number of fissions occurring in one generation equal to the number of fissions that occurred in the previous generation. In this scenario, the chain reaction is said to be stable and the reactor system is said to be critical.

If the multiplication factor is less than 1, the number of fissions decreases with time and the chain reaction is said to be convergent tending to extinction. The system in this case is said to be subcritical.

Nuclear reactors are devices or systems in which the fission chain reaction is achieved in a controlled manner. To control the fission chain reaction, the multiplication factor is varied accordingly. To achieve a multiplication factor of 1 and also operate the reactor for 18 to 24 months, a nuclear reactor is always charged with more fuel than necessary to compensate for consumed materials and accumulated poisons so as to sustain the chain reaction.

2.4.6 Reactor Control Mechanism

The desired value of the multiplication factor and degree of criticality in a reactor can be achieved by effectively deploying control mechanisms. Control mechanisms involve the use of control rods, soluble high absorbing materials dissolved into the moderator and also high absorption materials that are introduced into the fuel rods. These systems have negative effects on neutron population in the core and are said to introduce negative reactivity into the reactor core. Control rods are made up with materials that have high neutron absorption cross section and when in the reactor core, they alter the multiplication factor. When they are inserted into the core, the reactor becomes subcritical and when they are withdrawn, the reactor becomes supercritical. Control mechanisms lead to the distortion of the neutron flux profile through the absorption of neutrons.



For practical purposes, a closely related term, Reactivity is used rather than multiplication factor. Reactivity denotes the reactor capability to multiply the neutron population. The relationship between reactivity and multiplication factor is as follows,

$$\rho = \frac{(k-1)}{k}$$

$$k < 1 \Rightarrow \rho < 0$$
$$k = 1 \Rightarrow \rho = 0$$
$$k > 1 \Rightarrow \rho > 0$$

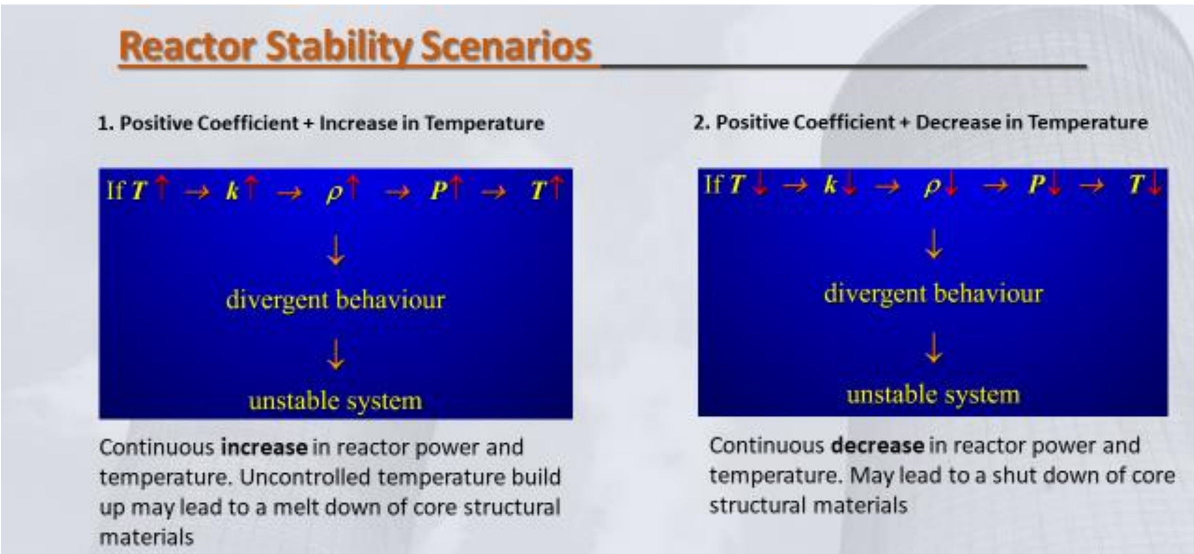
2.4.7 Reactor Stability

Another important variable that affects reactor criticality is the operating temperature. The multiplication factor is dependent on various parameters which at the same time vary depending on temperature**.** Temperature decisively affect reactivity. The extent to which reactivity is affected by changes in temperature is described in terms of Temperature Coefficient of Reactivity or Temperature Feedback Coefficient or simply Temperature Coefficient.

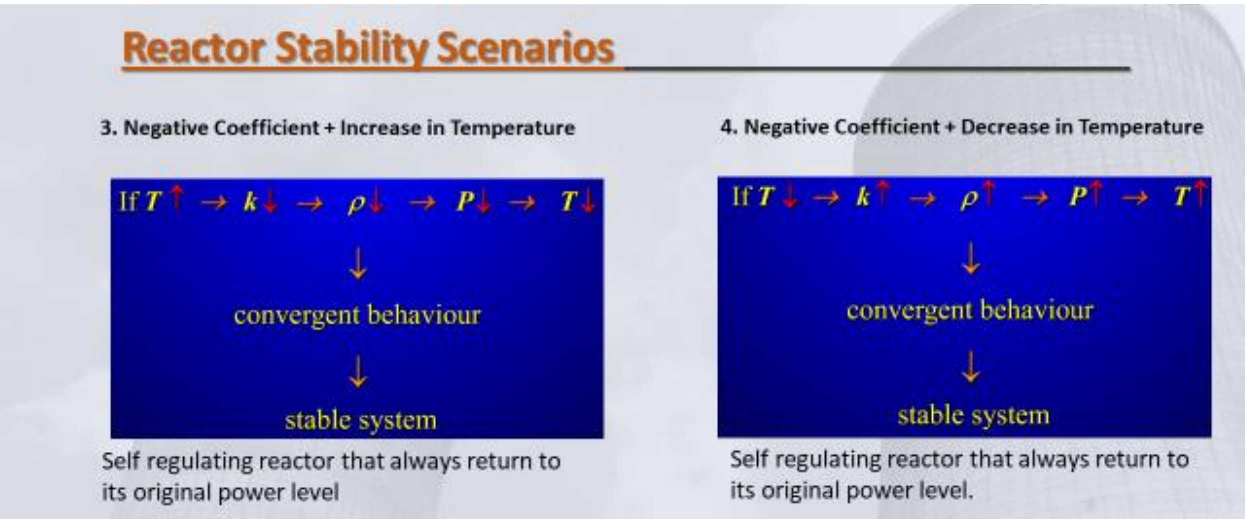
The temperature coefficient of reactivity is a product of the multiplication factor variation expressed as a fraction and the degree of temperature variation. ie.

$$\alpha_T \equiv \frac{dk}{k}\frac{1}{dT}$$

The temperature coefficient of reactivity is directly related to reactor stability and should always be negative at all reactor operating conditions.



Note that in both cases, the reactor is inherently unstable and such operations are not recommended.



In cases 3 and 4, the reactor is inherently stable and such operations are the only recommended operations of a nuclear reactor.

2.4.8 Interaction of Radiation with Matter

We live in a planet full of natural radiations which are present in soil, rocks, the air we breathe, the water we drink and also even in our bodies. These natural radiations make up the bulk of the total radiations we are exposed to everyday. We are also exposed to artificial radiations including, medical tests like x-rays and also radionuclides.

Radiations cannot be seen, smell, heard or touched. They can however be measured using radiation detecting devices such as the Geiger Counters. The count from the Geiger Counters is used to determine the dose. The dose expresses the quantity of a particular type of radiation exposed to a particular type of organ in the body. Dose is measured in Sievert (Sv) or MilliSievert (MSv). Nuclear energy workers wear dosimeters, a small device that measures radiation doses they are exposed to. This ensures that they are monitored so that they do not exceed their allowable dose limits.

Since radiations have the potential to cause harm, they must be strictly regulated. In Ghana, the Nuclear Regulatory Authority is mandated to regulate the use of nuclear energy and materials to protect health, safety, security and the environment.

Radiations released into the environment interact with matter in a number of processes including,

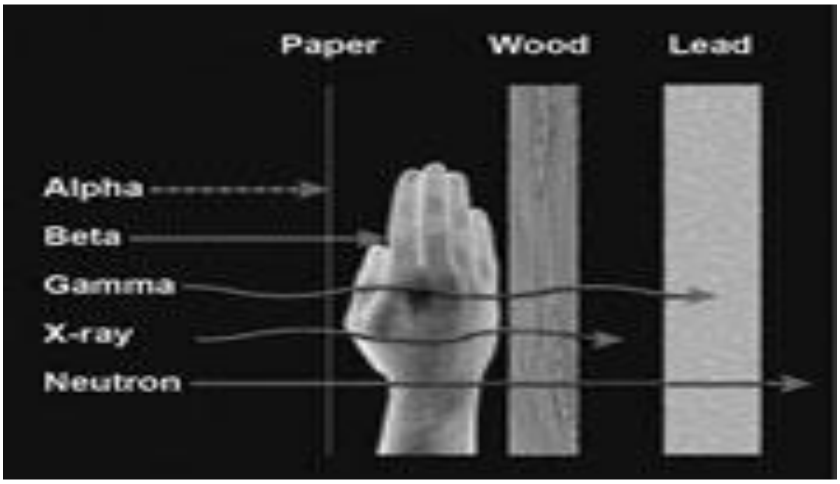
a. Penetration
b. Absorption (photoelectric effect)
c. Scattering
d. Pair production (electron and positron pair production) and
e. Photodisintegration.

The interaction depends on:
(i) The energy and the type of radiation and
(ii) The material characteristics: density (ρ), thickness (t) & atomic number (Z)

Some of these are discussed in this session.

1. **Penetration**

The different kinds of radiation travel different distances and have different abilities to penetrate matter, depending on their mass and their energy. The figure below shows the differences.



Neutrons, because they don't have any charge, don't interact with materials very well and travel a very long way. The only way to stop them is with large quantities of water or other materials made of very light atoms.

Alpha particles, because they are very heavy and have a very large charge, don't travel far at all. An alpha particle can't even get through a sheet of paper. Alpha particles outside the human body can't even penetrate the surface of the skin. The ability to stop alpha particles so easily is useful in smoke detectors, because a little smoke in a chamber is enough to stop the alpha particle and trigger an alarm.

Beta particles travel a little farther than alpha particles. A relatively small amount of shielding can stop them. They can get into the body but can't go all the way through. To be useful in medical imaging, beta particles must be released by a material that is injected into the body. They can also be very useful in cancer therapy if you can put the radioactive material in a tumour.

Gamma rays and x-rays can penetrate through the body. This is why they are useful in medicine—to show whether bones are broken or where there is tooth decay, or to locate a tumour. Shielding with dense materials like concrete and lead is used to avoid exposing sensitive internal organs or the people who may be working with this type of radiation. For example, the technician who does dental x-rays puts a lead apron over the patient before taking the picture. That apron stops the x-rays from getting to the rest of the patient's body. The technician stands behind the wall, which usually has some lead in it, to protect him or herself.

2. **Photoelectric Effect**

This is the dominant interaction mechanism for low energy photons. It involves an interaction of a photon with an atom as whole. The photon disappears in the process after giving up all its energy and an electron form the k-shell is ejected from the atom.

Photoelectric effect is the emission of electrons when electromagnetic radiation interacts with matter (mostly the surface of a metal or a conductor). The process occurs when a photon is totally absorbed by an inner shell (mostly K-shell) electron in an atom leading to the emission of the electron and also resulting in the formation of a positive ion. The process is also known as photoemission and the electrons emitted in this manner are called photoelectrons. In terms of behaviour and properties, photoelectrons are not different from other electrons.

Photons have characteristic energy, called photon energy, which is proportional to the frequency of the electromagnetic radiation. When an electron within some material absorbs the energy of a photon and acquires more energy than its binding energy, it is ejected. The photon disappears and the kinetic energy imparted to the photoelectron is equal to the energy of the incident photon minus that used to overcome the binding energy of the electron. If the incident photon energy is too low, the electron is unable to escape the material. For a given metal surface, there exists a certain minimum frequency of incident radiation below which no photoelectrons are emitted. This frequency is called the **threshold frequency**. Increasing the frequency of the incident beam beyond the threshold frequency increases the maximum kinetic energy of the emitted photoelectrons. In many cases the photoelectron loses energy by ionization of other atoms and in x-ray diagnosis for example, this contributes to patient dose or exposure. Also the electron deficiency created (usually in the K shell) after the ejection of the electron is instantly filled, usually by an L- or M- shell electron, with the release of characteristic radiation. Whatever the shell of the replacement electron, the characteristic photons generated are of such low-energy that they are all absorbed within the patient and do not fog the film. The photoelectrons ejected, also travel only a short distance in the absorber before they give up their energy. As a consequence, all the energy of incident photons that undergo photoelectric interaction is deposited in the patient. This is beneficial in producing high-quality radiographs, because no scattered radiation fogs the film, but potentially deleterious for patients because of increased radiation absorption.

3. **Scattering**

There are two types of scattering depending on energy transfer; coherent (Rayleigh) scattering and incoherent (Compton) scattering.

Coherent (Rayleigh) Scattering may occur when a low-energy incident photon passes near an outer electron of an atom (which has a low binding energy). The incident photon interacts with the electron in the outer-shell by causing it to vibrate momentarily at the same frequency as the incoming photon. The incident photon then ceases to exist. The vibration causes the electron to radiate energy in the form of another photon with the same frequency and energy as in the incident photon. In effect the incident photon only changes direction (scatter) without losing energy. Because no energy is transferred to the atom, no ionization occurs. The process occurs with low energy electromagnetic radiation whose photons do not have enough energy to liberate the electron from its bound state (i.e. the photon energy is well below the binding energy of the electron). No energy transfer means there is no energy deposition and thus no dose or exposure results from coherent scattering. Coherent scattering is not a major interaction process encountered in radiography at the energies normally used. It contributes very little to staff dose and film fog because the total quantity of scattered photons is small and its energy level is too low for much of it to reach the film.

Compton Scattering is dominant in intermediate photon energies. During Compton Effect, a photon interact with an outer orbital electron. After transferring its energy to the electron which is ejected, the photon is scattered and leaves with a low energy at an angle.

Compton scattering occurs when a photon interacts with a loosely bound (outer shell) electron, which receives kinetic energy from the photon and is ejected from the point of impact. This results in a scattered photon that has less energy than the incident photon and travels in a new direction. The energy of the scattered photon equals the energy of the incident photon minus the kinetic energy gained by the ejected electron plus its binding energy. The higher the energy of the incident photon, the greater the probability that the angle of scatter of the scattered photon will be small and its direction will be forward. Scattered photons may move in any direction, including 180 degrees to the direction of the incident photon (backscattered). The lower the angle of deflection, the lower the energy transferred to the ejected electron and the higher the energy retained by the scattered photon. Energy transferred to the electron is maximum when the photon is backscattered.
As with photoelectric absorption, Compton scattering results in the loss of an electron and ionization of the absorbing atom leaving a positive ion. The ejected electron in turn loses energy by ionizing other atoms in the tissue and contributing to patient dose.
Scattered Photons in Compton interactions account for most of the scattered radiation in x-ray diagnosis leading to staff dose and film fog For example approximately 30% of the scattered photons formed during a dental x-ray exposure (primarily from Compton scattering) exit the patient's head. This is advantageous to the patient because some of the energy of the incident x-ray beam escapes the tissue, but it is disadvantageous because it causes nonspecific film darkening (or fogging of the film). Scattered photons darken the film while carrying no useful information to it.

4. **Pair Production**

Pair Production occurs only for gamma rays of high energy. By this effect, the gamma ray is transformed to matter in the form of a pair of negatively and positively charged electrons (negatron and positron).

Pair production occurs when a high energy photon interacts with the nucleus of an atom. The photon disappears, and the energy is converted to an electron and a positron. Pair production has a photon energy threshold of 1.022 MeV, which is the energy required to produce an electron (.511Mev) and positron (.511MeV) pair. Because of this high threshold energy (1.022Mev) .pair production is not encountered in x-ray diagnosis but is important in Mega voltage radiotherapy.

5. **Positron Annihilation**

In this process, a positron collides with an electron resulting in the annihilation of both particles. Electrons and positrons are of equal mass but opposite charge.

6. **Photodisintegration**

Photodisintegration occurs when a high energy photon is absorbed by the nucleus of an atom, resulting in the immediate disintegration of the nucleus. The energy threshold for photodisintegration is 15Mev. Photodisintegration is, therefore, only important at high photon energies encountered in Mega voltage radiotherapy and accelerator physics.

The three major forms of interaction of radiation with matter which are of clinical importance in radiotherapy are, Compton Effect, Photoelectric Effect and Pair Production. Out of these, the Compton effect is the most important in modern day megavoltage radiation therapy. The

Photoelectric effect is of primary importance in diagnostic radiology and has only historical importance in present day radiotherapy.

2.4.9 Attenuation

Attenuation is the gradual reduction in the intensity of a radiation as it travels through matter. It is a common phenomenon experienced by any kind of radiation propagating through a medium. For example, sunlight is attenuated by dark glasses, water and air attenuate both light and sound at variable attenuation rates, X- rays are attenuated by lead, and seismic waves are attenuated as they propagate through the Earth. Normally, attenuation is an exponential function of the path length through the medium. In other words, the extent of the attenuation of a wave through a given medium depends on the path length. The thickness of a material that attenuates a photon beam (e.g. x-rays) by 50 % is the half value layer (HVL) and the thickness that attenuates a photon beam (x-rays) by 90 % is called the tenth value layer (TVL) because it transmit only 10% of the incident photons.
In addition, the attenuation of a wave or beam depends on the frequency and intensity of the wave and the medium through which the wave propagates. The higher the frequency and intensity of the radiation the lower the attenuation. The units of measuring attenuation are dB/m, dB/cm or dB/km (decibels per unit path length).
The extent of the attenuation of electromagnetic waves depends on the medium through which the waves propagate. For instance, the extent of attenuation of a given electromagnetic wave through water and a plasma is very different. The attenuation of electromagnetic waves occurs due to both absorption and scattering of photons. The absorption of electromagnetic waves in a matter is a result of several types of interactions (photoelectric effect, Compton Effect, pair production) that take place between electromagnetic waves and matter.
Attenuation is a very important factor in telecommunication as the attenuation limits the effective range of signals. In fibre optics, the attenuation of signals through the medium is commonly known as the transmission loss. Fibre optic technology is widely being used for long- range communication as the attenuation in optical fibres is notably low compared to other communication technologies.
Attenuation of ultrasound waves in a given medium is the reduction in amplitude of the waves traveling through the medium and, depends on the medium, the path length and the frequency of the waves. The extent of the attenuation determines the quality of images. Therefore, attenuation of ultrasound waves is a very important factor in ultrasound imaging.

As radiation travels through a medium and gets attenuated, the energy lost by the radiation is deposited in the medium.

2.4.10 Linear Energy transfer (LET)

Linear Energy Transfer represents the energy absorbed by a medium per unit length of travel (keV/μm). For a given medium, LET is proportional to the square of the particle charge (q^2) and inversely proportional to particle Kinetic Energy. Thus, low speed particles with multiple charges, such as slow moving alpha particles, have high LET values. Neutrons, protons, alpha particles, and heavy ions are high LET radiations with values ranging from 3 - 200 keV/μm.
Photons, gamma rays, x-rays and electrons, are low LET radiations with values ranging from 0.2 - 3 keV/μm.
High LET radiations are much more effective in producing biological damage than low LET radiation.

2.4.11 Biological Effects of Ionizing Radiations

Radiation has a wide range of benefits but presents some health hazards if proper measures against excessive exposure are not taken. When radiation passes into an absorbing medium such as body tissues, some of the energy carried by the radiation is transferred to the medium where it may produce biological damage. The energy deposited per unit mass of the medium is known as the **absorbed dose** and is a very useful quantity for the prediction of biological effects. The events that result in this absorbed dose and subsequent biological damage are quite complicated. Radiation damage to tissue and/or organs depends on the dose of radiation received, or the absorbed dose which is expressed in a unit called the gray (Gy). The potential damage from an absorbed dose depends on the type of radiation and the sensitivity of different tissues and organs.

The effective dose is used to measure ionizing radiation in terms of the potential for causing harm. The sievert (Sv) is the unit of effective dose that takes into account the type of radiation and sensitivity of tissues and organs. It is a way to measure ionizing radiation in terms of the potential for causing harm. The Sv is a very large unit so it is more practical to use smaller units such as millisieverts (mSv) or micro Sieverts (μSv). There are one thousand μSv in one mSv, and one thousand mSv in one Sv. In addition to the amount of radiation (dose), it is often useful to express the rate at which this dose is delivered (dose rate), such as micro Sieverts per hour (μSv/hour) or millisievert per year (mSv/year).

Beyond certain thresholds, exposure to ionizing radiation can cause cell damage to living tissues and can impair the normal functioning of tissues and/or organs. High acute doses can produce acute effects such as skin redness, hair loss, radiation burns, or acute radiation syndrome. These effects are more severe at higher doses and higher dose rates. For instance, the dose threshold for acute radiation syndrome is about 1 Sv (1000 mSv).

If the radiation dose is low and/or it is delivered over a long period of time (low dose rate), the risk is substantially lower because there is a greater likelihood of repairing the damage. There is still a risk of long-term effects such as cancer, however, that may appear years or even decades later. Effects of this type will not always occur, but their likelihood is proportional to the radiation dose. This risk is higher for children and adolescents, as they are significantly more sensitive to radiation exposure than adults.

Epidemiological studies on populations exposed to radiation, such as atomic bomb survivors or radiotherapy patients, showed a significant increase of cancer risk at doses above 100 mSv. More recently, some epidemiological studies in individuals exposed to medical exposures during childhood (paediatric CT) suggested that cancer risk may increase even at lower doses (between 50-100 mSv).

Prenatal exposure to ionizing radiation may induce brain damage in foetuses following an acute dose exceeding 100 mSv between weeks 8-15 of pregnancy and 200 mSv between weeks 16-25 of pregnancy. Before week 8 or after week 25 of pregnancy human studies have not shown radiation risk to fetal brain development. Epidemiological studies indicate that the cancer risk after fetal exposure to radiation is similar to the risk after exposure in early childhood.

Stochastic effect is a radiation-induced health effect, generally occurring without a threshold level of dose, whose probability is proportional to the dose and whose severity is independent of the dose. Examples include cancer such as leukaemia

The probability of occurrence of cancer is higher for higher doses, but the severity of any cancer that may result from irradiation is independent of the dose.

Deterministic effect is a radiation-induced health effect that will not occur below a certain threshold level of dose. Above that threshold dose the severity of the effect is directly related to the magnitude of the dose received and the part of the body exposed. Examples include Cataract, sterility, vomiting, hair loss, skin burns and death

Acute Exposure refers to a dose received over a short period of time leading to deterministic effects.

Chronic Exposure refers to a dose received over a long period of time leading to stochastic effects.

Radiation exposure in humans may be internal or external, and can be acquired through various exposure pathways.

Internal exposure to ionizing radiation occurs when a radionuclide is inhaled, ingested or otherwise enters into the bloodstream (for example, by injection or through wounds). Internal exposure stops when the radionuclide is eliminated from the body, either spontaneously (such as through excreta) or as a result of a treatment.

External exposure may occur when airborne radioactive material (such as dust, liquid, or aerosols) is deposited on skin or clothes. This type of radioactive material can often be removed from the body by simply washing. External exposure to ionizing radiation can also result from irradiation from an external source, such as medical radiation exposure from X-rays. External irradiation stops when the radiation source is shielded or when the person moves outside the radiation field.

People can be exposed to ionizing radiation under different circumstances, at home or in public places (public exposures), at their workplaces (occupational exposures), or in a medical setting (as are patients, caregivers, and volunteers). Exposure to ionizing radiation can be classified into 3 exposure situations.

The first, planned exposure situations, result from the deliberate introduction and operation of radiation sources with specific purposes, as is the case with the medical use of radiation for diagnosis or treatment of patients, or the use of radiation in industry or research.

The second type of situation, existing exposures, is where exposure to radiation already exists, and a decision on control must be taken – for example, exposure to radon in homes or workplaces or exposure to natural background radiation from the environment.

The last type, emergency exposure situations, result from unexpected events requiring prompt response such as nuclear accidents or malicious acts.

2.5 Why Nuclear

With world population expected to grow 25 percent in the next 20 years, the demand for electricity is expected to nearly double by 2030. To meet that demand, the supply of safe, clean and reliable electricity is essential. Increased economic output and improved standards of living will put a strain on the current energy supply, and with such a significant increase in energy demand, carbon emissions and other greenhouse gasses must be reduced to avoid any additional negative environmental impact.

Nuclear energy is the largest source of clean, reliable, affordable and sustainable energy and no other source can come close to its generating capacity. Nuclear is often left out of the "clean energy" conversation despite it being the second largest source of low-carbon electricity in the world behind hydropower. Nuclear is a zero-emission clean energy source and thus protect the air quality.

The use of nuclear power plants replaces such technologies that use fossil fuels and that produces tons of harmful air pollutants each year and so contribute to acid rain, smog, lung cancer and cardiovascular diseases. Nuclear power plants don't produce nitrous oxide or sulfur dioxide that could threaten our atmosphere and environment. It also doesn't produce carbon dioxide or other greenhouse gases that impact climate change.

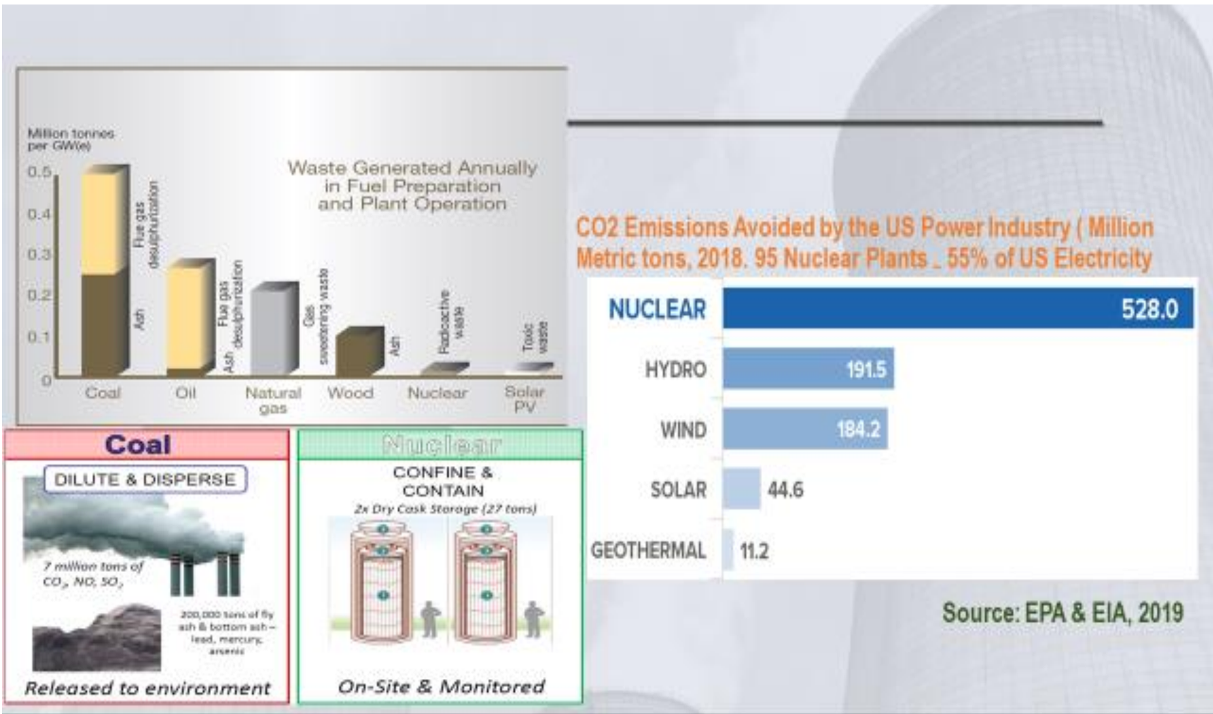


Figure 16: Nuclear is Clean Technology

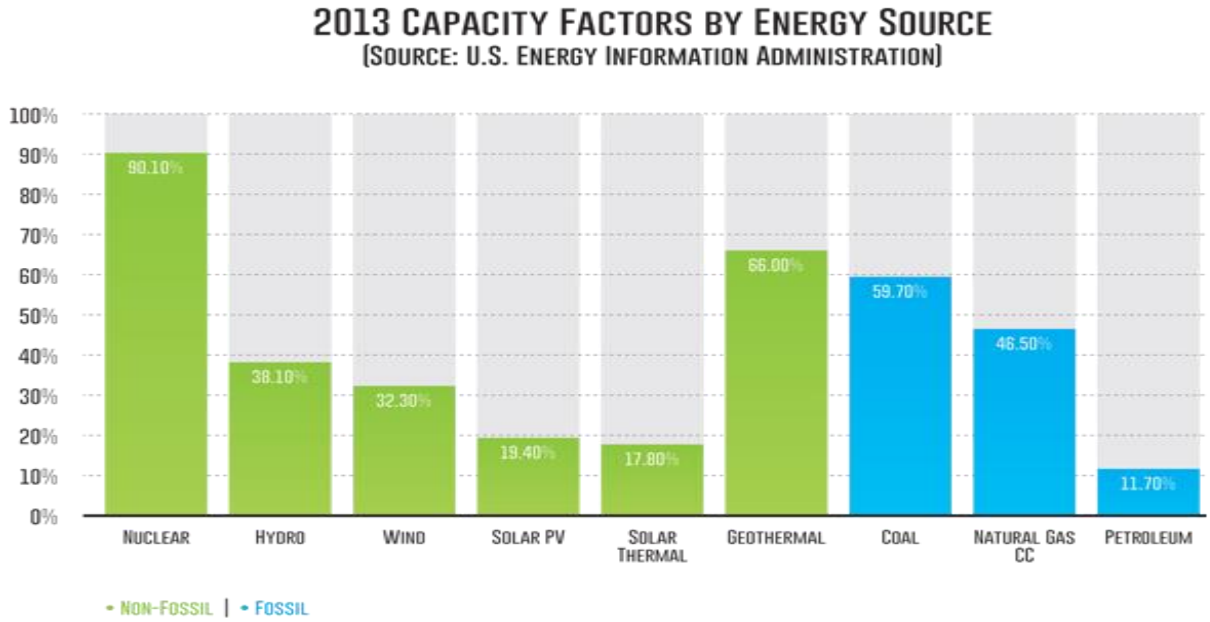
Figure 16 (a): Emissions from Thermal Power Plants

Despite producing massive amounts of carbon-free power, nuclear energy produces more electricity on a smaller land size than any other clean-air source. Nuclear energy promotes land and habitat preservation. Nuclear power plants produce a large amount of electricity in a relatively small space and they require significantly less land for their sites and operations than other energy sources such as wind.

Nuclear energy promotes wildlife conservation because the areas around nuclear plants and their cooling ponds are so clean, they are often developed as wetlands that provide nesting areas for water fowl and other birds, new habitats for fish, and the preservation of other wildlife.

Nuclear has the highest capacity factors, or availability, of any source of electricity. It's available 90 percent of the time, compared to 34 percent for wind and just 25 percent for solar. No other generating source is more reliable than nuclear energy. Unlike intermittent sources such as wind and solar, nuclear energy provides electricity day and night. Looking at capacity factors makes it clear that no other source comes close to the level of availability that nuclear provides.

Figure 17: 2013 Capacity Factors



Nuclear has the lowest production costs of any generating source. Uranium, used to make nuclear fuel, has stable prices and is abundant worldwide, thus providing a high degree of energy security.

Figure 18: Nuclear is Affordable Technology

Nuclear energy contributes to national energy security. As an integral part of the energy mix in countries that operate nuclear power plants, it’s a secure energy source that nations can rely upon. It’s not subject to unreliable weather or climate conditions, unpredictable cost fluctuations, or dependence on supply from unstable countries. And, the security of supply is excellent, with extensive fuel supply sources around the globe.

Nuclear is Resilient Technology

	Fuel Price	Climate Variabilities Natural Events	Waste & Environment	Availability
Nuclear	Stable fuel price Rep. 19% of total gen. cost and in small quantity for production	Plant cooling may be affected by high water temp. & drought Withstands flooding, earthquakes, tornados	Small quantity of radioactive waste rigorously stored (Green)	Operate 18-24 months before Refueling Outage for 35 days. 40 – 60 years with possible life extended
Coal	Volatile fuel price Rep. 78% of total generation cost High volumes of fuel required for production	Plant may be affected by flooding, drought, high water temp. Cannot withstand earthquakes & tornados	High volumes of green house gas emission. High volumes of pollutants during coal mining and wet scrubbing (Not Green)	35 - 40 years
Oil & Gas	Volatile fuel price Rep. 98% of total generation cost High volumes of oil & Gas required for production	Plant may be affected by flooding, drought, high water temperature Cannot withstand earthquakes & tornados	High volumes of green house gas emissions in the atmosphere (Not Green)	30 – 35 years
Solar & Wind	-	Plant availability affected by flooding, dust, humidity Cannot withstand earthquakes & tornados	High volumes of waste and chemicals from batteries that are improperly disposed (Green)	18 – 20 years

Figure 19: Nuclear is Resilient Technology

Nuclear energy plays a key role in helping to provide stable electricity supply. Nuclear power plants are designed to operate continuously for long periods of time, and they run about 540 to 730 days before they are shut down for refueling. All nuclear power plants have extensive safety systems, backup systems and instrumentation and controls to maintain safe plant operating conditions.

One nuclear power plant requires 400,000 cubic yards of concrete, 66,000 tons of steel, 44 miles of piping, 300 miles of electric wiring and 130,000 electrical components. That's quite a lot of jobs touching a number of industries. At the peak of construction, as many as 3,500 construction workers are required. Operating nuclear plants also have a positive economic impact. They typically employ about 600 well paid workers who operate and maintain the plant. They in turn help to sustain the communities where they work and live as a consumer and tax payer. With the continued development of new nuclear plants all around the world, the nuclear industry is expected to hire more than 20,000 workers over the next five years. The jobs that are created and sustained and the local industries that are involved and get expanded as a result are just another reason why nuclear energy is vital.

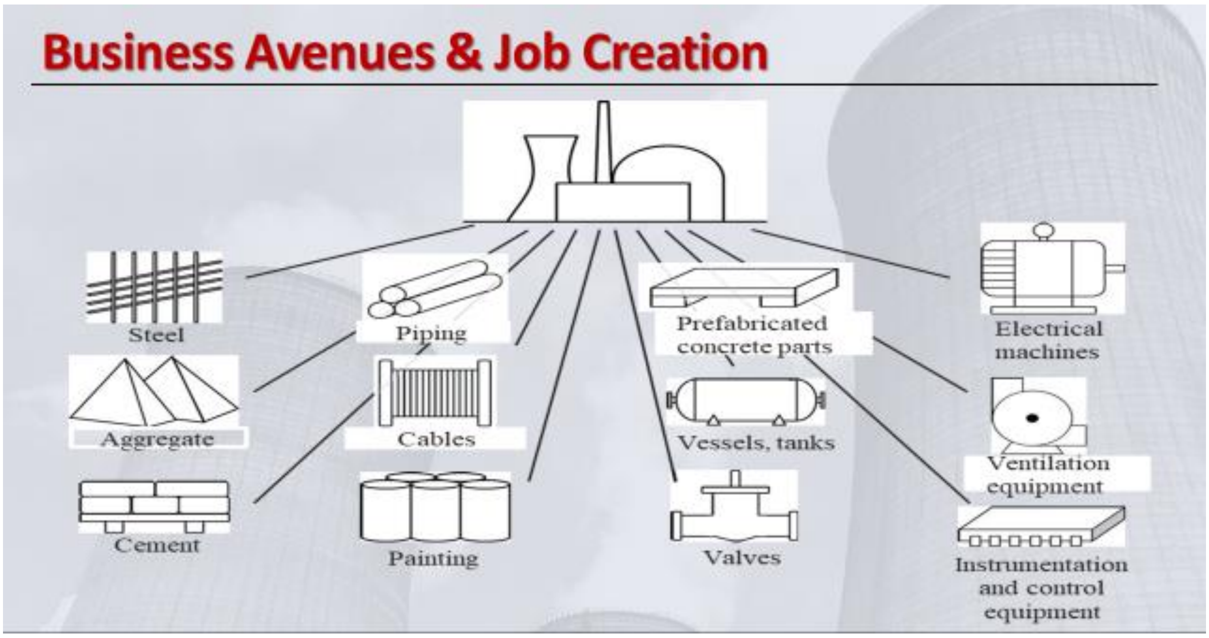


Figure 20: Nuclear creates business and Jobs

2.6 Key Organizations
2.7 Milestones
2.8 Infrastructural Issues and their Relevance
2.9 Stakeholders and their Roles and Responsibilities
2.10 The International Atomic Energy Agency

6.1 Ghana's Generation Mix and Challenges

6.2 Ghana's Nuclear Journey

GHANA'S NUCLEAR JOURNEY

1963 – 1967

- Ghana's 1st Reactor Project Launched: Construction of 2MW Soviet Research Reactor started
- Ghana Atomic Energy Commission (GAEC) established
- Reactor project suspended after the overthrow of Government
- Government invited Sir John Douglas Cockcroft and IAEA to review Ghana's Reactor Project
- Ghana's Reactor Project reviewed by Sir Cockcroft and report noted: " In view of the capacity of the Volta Hydro Electric Project, for some 20 years to come, a reactor is unlikely to be necessary for the purpose of producing power"
- Reactor Project cancelled and GAEC shut down

1973 - 2006

- GAEC revived to continue R&D in Nuclear Science and Technology
- Effort made to acquire 1MW Research Reactor from the Federal Republic of Germany truncated due to 1973 coup d'etat
- GAEC commissioned a Chinese built 30kW research reactor under IAEA Technical Cooperation Agreement in 1995
- GAEC & University of Ghana with IAEA support established Post Graduate School of Nuclear and Allied Sciences in 2006
- Three (3) Major Power crises experienced in 1984, 1998 and 2006
- A minor Power crisis experienced in 1993

2007 - 2012

- Presidential Committee (Adzei Bekoe Committee) established to report on feasibility of re-introducing Nuclear Power into the country's energy mix
- Committee's report recommended Government to pursue Nuclear Power inclusion in the energy mix
- Cabinet decided to include Nuclear Power in the energy mix in 2008
- Nuclear Energy included in National Energy Policy and Strategy
- Ghana Nuclear Power Programme Organisation (GNPPO) established to oversee the development of the Nuclear Power Programme in 2012
- National working group on Nuclear Power Infrastructure development established

2013 - 2015

- Working groups established at GAEC to focus on Nuclear Programme Infrastructure development
- Nuclear Power Centre (NPC) established at GAEC as the Technical driving force for GNPPO
- IAEA experts visited Ghana to develop a better understanding of the Nuclear Power Infrastructure development
- Roadmap for Nuclear Power Infrastructure development in Ghana established
- Act, 2015 (Act 895) passed for the established of an effective and independent nuclear regulatory body - Nuclear Regulatory Authority

2016 - 2017

- NPC upgraded to an institute, 'Nuclear Power Institute'
- Ghana requested for IAEA integrated Nuclear Infrastructure Review (INIR) Mission for Phase 1 of programme development
- Ghana submitted Phase 1 INIR Mission Self - Evaluation report to IAEA for review
- Phase 1 INIR Mission conducted by IAEA
- IAEA submitted Phase 1 INIR Mission Report to Government
- Ghana developed Phase 1 Integrated Work Plan (IWP) with IAEA
- Stakeholder consultation on Owner/Operator establishment held

2018 - 2019

- GNPPO addressed INIR Phase 1 recommendations and suggestions
- GNPPO submitted a Memo to Cabinet on the establishment of Owner/Operator organisation
- Nuclear Power Ghana (NPG) as Owner/Operator organisation established with a governing Board
- Four candidate Sites identified
- Ghana requested for IAEA Phase 1 INIR Follow-up Mission
- Phase 1 INIR Follow-up Mission conducted by IAEA
- Phase 1 Nuclear Programme Comprehensive Report (NCR) developed and submitted
- NPG incorporated under the Company's Act, 1963 (Act 179)

6.3 Status of Ghana's Nuclear Power Programme
6.4 Role and Function of the Nuclear Power Institute
6.5 Role and Function of the Nuclear Power Ghana
6.6 Role and Function of the Nuclear Regulatory Authority

CHAPTER FIVE: Legal and Regulatory Framework

5.1 Risk and Benefits

As is well known, nuclear energy poses special risks to the health and safety of persons and to the environment: risks that must be carefully managed. However, nuclear material and technology also hold the promise of significant benefits, in a variety of fields, from medicine and agriculture to electricity production and industry. A human activity that involves only hazards and no benefits calls for a legal regime of prohibition, not regulation. Thus a basic feature of nuclear energy legislation is its dual focus on risks and benefits.

5.2 **National legal hierarchy**

It is important to recognize that legal norms for the regulation of nuclear energy are part of a State's general legal system. Nuclear law must take its place within the normal legal hierarchy applicable in most States. This hierarchy consists of several levels. The first, usually referred to as the constitutional level, establishes the basic institutional and legal structure governing all relationships in the State. Immediately below the constitutional level is the statutory level, at which specific laws are enacted by a parliament in order to establish other necessary bodies and to adopt measures relating to the broad range of activities affecting national interests. The third level comprises regulations; that is, detailed and often highly technical rules to control or regulate activities specified by statutory instruments. Owing to their special character, such rules are typically developed by expert bodies (including bodies designated as regulatory authorities) empowered to oversee specific areas of national interest, and promulgated in accordance with the national legal framework. A fourth level consists of non-mandatory guidance instruments, which contain recommendations designed to assist persons and organizations in meeting the legal requirements. Depending on which nuclear activities a State decides to sanction, the exploitation of nuclear technology can involve the application of a wide variety of laws primarily relating to other subjects (such as environmental protection, industrial safety, land use planning, administrative procedure, mining, transport, government ethics and electricity rate regulation). In general, deviations from the general framework of national legislation should be accepted only where the special character of an activity warrants special treatment. Therefore, to the extent that a nuclear related activity is adequately covered in other laws, it should not be necessary to promulgate new legislation. However, from the earliest days of its development, nuclear energy has been considered to require special legal arrangements in order to ensure that it is properly managed.

5.3 DEFINITION OF NUCLEAR LAW

Nuclear law can be defined as: The body of special legal norms created to regulate the conduct of legal or natural persons engaged in activities related to fissionable materials, ionizing radiation and exposure to natural sources of radiation. This definition comprises four key elements. First, as a body of special legal norms, nuclear law is recognized as a part of general national legislation, while at the same time comprising different rules required by the special nature of the technology. Second, the element of regulation incorporates the risk–benefit approach that is central to managing activities that present both hazards and advantages for social and economic development. Third, as with all legal regimes, the special legal norms relate to the conduct of legal persons, including commercial, academic, scientific and governmental entities, as well as of individuals. The fourth element focuses on radioactivity (produced through the use of fissionable material or ionizing radiation) as the defining feature justifying a special legal regime

5.4 **OBJECTIVE OF NUCLEAR LAW**

Before attempting to identify which special aspects of nuclear law distinguish it from other types of law, it is important to highlight briefly the fundamental reason why a State would decide to make the major effort necessary in order to promulgate such legislation. Simply stated, the primary objective of nuclear law is:

To provide a legal framework for conducting activities related to nuclear energy and ionizing radiation in a manner which adequately protects individuals, property and the environment.

In light of this objective, it is particularly important that responsible authorities carefully assess their current nuclear energy activities and their plans for future nuclear energy development so that the legislation ultimately adopted is adequate

5.5 **PRINCIPLES OF NUCLEAR LAW**

The characteristics of nuclear law that distinguishes it from the other aspects of national law are a number of basic concepts, often expressed as fundamental principles. These principles are:

(a) The safety principle;

(b) The security principle;

(c) The responsibility principle;

(d) The permission principle;

(e) The continuous control principle;

(f) The compensation principle;

(g) The sustainable development principle;

(h) The compliance principle;

(i) The independence principle;

(j) The transparency principle;

(k) The international co-operation principle.

5.5.1 Safety Principle

Numerous national laws, international instruments, regulatory documents and expert commentaries have emphasized that safety is the primary requisite for the use of nuclear energy and the applications of ionizing radiation. In discussions on nuclear safety, a number of subsidiary principles have been articulated. One such principle has been labelled the ‘prevention principle’. It holds that, given the special character of the risks of using nuclear energy, the primary objective of nuclear law is to promote the exercise of caution and foresight so as to prevent damage that might be caused by the use of the technology and to minimize any adverse effects resulting from misuse or from accidents. A complementary principle is the ‘protection principle’. The fundamental purpose of any regulatory regime is to balance social risks and benefits. Where the risks associated with an activity are found to outweigh the benefits, priority must be given to protecting public health, safety, security and the environment. Of course, in the event that a balance cannot be achieved, the rules of nuclear law should require action favouring protection. It is in this context that the concept commonly referred to as the ‘precautionary principle’ (i.e. the concept of preventing foreseeable harm) should be understood. In applying these related and overlapping safety concepts, it is always important to return to the fundamental requirement that both the risks and the benefits of nuclear energy be well understood and taken into account with a view to achieving a sensible balance in the framing of legal or regulatory measures. Fundamental safety principles codified in legislation may be applied to a wide variety of activities and facilities that pose very different types and levels of risk. Activities posing significant radiation hazards will obviously require stringent technical safety measures and, in parallel, strict legal arrangements. Activities posing little or no radiation hazard will need only elementary technical safety measures, with limited legal controls. The law should reflect the hierarchy of risk. Indeed, legal restrictions that cannot be justified by the risk posed by a certain activity may be deemed an undue limitation on the rights of the persons or organizations conducting that activity.

5.5.2 Security Principle

In developing a legislative framework for peaceful nuclear activities, it may be useful to recall that the modern development of nuclear technology had its origins in the military programmes of several States. Just as certain nuclear material and technologies pose health and safety risks if diverted to non-peaceful ends, they also pose risks to the security of persons and social institutions. Lost or abandoned radiation sources can cause physical injury to persons unaware of the associated hazards. The acquisition of radiation sources by terrorist or criminal groups could lead to the production of radiation dispersion devices, to be used to commit malevolent acts. The diversion of certain types of nuclear material could contribute to the spread of nuclear explosives to both subnational and national entities. For these reasons, special legal measures are required to protect and account for the types and quantities of nuclear material that may pose security risks. These measures must protect against both accidental and intentional diversion from the legitimate uses of these materials and technologies.

5.5.3 Responsibility Principle

The use of nuclear energy typically involves numerous parties, such as research and development organizations, processors of nuclear material, manufacturers of nuclear devices or sources of ionizing radiation, medical practitioners, architect–engineering firms, and construction companies, operators of nuclear installations, financial institutions and regulatory bodies. With so many parties potentially engaged in a nuclear related activity, a question that arises is: “Who is primarily responsible for ensuring safety?” In a sense, of course, all entities having some control over a nuclear related activity bear at least part of the responsibility for safety. However, the entity that has been consistently identified as primarily responsible is the operator or licensee who has been granted the authority to conduct specific activities related to nuclear energy or ionizing radiation. Legal arrangements have been developed under which a part or all the financial liability for the damage that could result from nuclear related activities may be assigned (or ‘channelled’) to different parties. However, the starting point for such arrangements is the fundamental principle that the operator or licensee should bear the burden of ensuring that its activities meet the applicable safety, security and environmental protection requirements.

5.5.4 Permission Principle

In most national legal systems, activities not specifically prohibited by law are considered to be free for persons to undertake without official authorization. Only if an activity poses an identifiable risk of injury to persons or to the environment is it appropriate for the law to require that prior permission be obtained before a person can conduct that activity. As a consequence of the special risks associated with nuclear technology, nuclear law normally requires that prior permission be obtained for activities involving fissionable material and radioisotopes. Various terms have been used for such permission, including ‘authorization’, ‘licence’, ‘permit’, ‘certificate’ or ‘approval’. In applying the permission principle, it is important for the law to identify clearly those activities or facilities that require an authorization, and those that do not. In cases in which the regulatory body has found that the risks associated with an activity are so low as to be below regulatory concern, a specific authorization may not be required. In such cases a general authorization can be issued in the form of an exemption set forth in a public document or in announcements. However, the regulatory authority always retains the ability to revoke such general authorizations if information comes to light suggesting that the risks of the activity are excessive. It must also be borne in mind that the issuance of an authorization to conduct a nuclear related activity can and typically does have practical and legal implications for third parties. For example, the rights of persons living in the vicinity of a proposed nuclear power plant could be affected by the issuance of a licence to construct the installation.

5.5.5 Continuous Control Principle

Even in circumstances in which an authorization (typically in the form of a licence) has been granted to conduct certain activities, the regulator must retain a continuing ability to monitor those activities so as to be sure that they are being conducted safely and securely and in accordance with the terms of the authorization. This principle means that national nuclear legislation must provide for free access by regulatory inspectors to all premises where nuclear material is being used and stored.

5.5.6 **Compensation Principle**

Depending on various technical factors, the use of nuclear energy poses the risk of major damage to persons, property and the environment. As preventive measures cannot completely exclude the potential for such damage, nuclear law requires that States adopt measures to provide adequate compensation in the event of a nuclear accident.

5.5.7 Sustainable Development Principle

A number of instruments in the field of environmental law have identified a duty for each generation not to impose undue burdens on future generations. The principle in question is that economic and social development can be ‘sustainable’ only if the world’s environment is protected. It has particular applicability in the nuclear field, because some fissile material and sources of ionizing radiation can pose health, safety and environmental risks for very long periods of time. However, the very long lived character of these materials has made it difficult to determine which current measures are necessary in order to protect generations adequately in the very remote and unpredictable future. One approach in applying the sustainable development principle in the nuclear field has been to urge that the current generation does whatever is possible for long term safety, but without foreclosing options for future generations and without relying unduly on long term forecasts, which are unlikely to be accurate over the extended timescales involved.

5.5.8 Compliance Principle

Although many human activities taking place within the territory of a State can result in damage beyond its borders, nuclear energy has been deemed to involve particular risks of radiological contamination transcending national boundaries. Both regionally and globally, bilateral and multilateral instruments are building an international law of nuclear energy. To the extent that a State has adhered to the international legal regimes in question, national nuclear law must reflect the obligations that they contain. Furthermore, a principle of customary international law has emerged to the effect that the territory of a State must not be used in such a way as to cause damage in another State and that, consequently, control measures are necessary. In States in which national law automatically adopts treaties to which those States have adhered as self-executing, no separate legislation may be needed. In many other States, however, compliance with international obligations requires additional legislative action.

5.5.9 Independence Principle

It is sufficient to note that nuclear law places particular emphasis on the establishment of a regulatory authority, whose decisions on safety issues are not subject to interference from entities involved in the development or promotion of nuclear energy. Given the significant risks associated with nuclear technology, other interests must defer to the regulator’s independent and expert judgement when safety is involved.

5.5.10. Transparency Principle

Nuclear energy saw much of its early development in military programmes originating in the Second World War. At that time, and for a substantial period afterwards, information concerning nuclear material and technology was considered highly sensitive and was treated by governments as confidential. With the development of the peaceful uses of nuclear energy, however, public understanding of and confidence in the technology have required that the public, the media, legislatures and other interested bodies be provided with the fullest possible information concerning the risks and benefits of using various nuclear related techniques for economic and social development. The transparency principle requires that bodies involved in the development, use and regulation of nuclear energy make available all relevant information concerning how nuclear energy is being used, particularly concerning incidents and abnormal occurrences that could have an impact on public health, safety and the environment.

5.5.11. International co-operation Principle

This principle relates to the need for the users of nuclear techniques and the regulators of nuclear activities to maintain close relationships with counterparts in other States and in relevant international organizations. The international dimension of nuclear energy is based on several factors. First, in the area of safety and the environment, the potential for trans boundary impacts requires governments to harmonize policies and develop co-operative programmes so as to reduce the risks of damage to their citizens and territories, the global population and indeed to the planet as a whole. Also, lessons learned in one State about how to enhance safety can be highly relevant to improving the situation in other States. It is vital to achieving improvements in the safety of nuclear activities and facilities worldwide that such lessons be promptly and widely shared. Second, the use of nuclear material involves security risks that do not respect national borders. Threats of terrorist acts and the threats associated with illicit trafficking in nuclear material and the proliferation of nuclear explosives have long been recognized as matters requiring a high level of international co-operation. Third, a large number of international legal instruments have been promulgated to codify the obligations of States in the nuclear field. Not only must governments comply in good faith with those obligations, but the terms of those instruments may limit the discretion of legislators in framing national legislation concerning some matters covered by them. Fourth, the increasingly multinational character of the nuclear industry, with frequent movements of nuclear material and equipment across national borders, makes effective control dependent on parallel and joint approaches by both public and private entities. For all these reasons, national nuclear energy legislation should make adequate provision for encouraging public bodies and private users of nuclear energy to participate in relevant international activities in the nuclear field.

5.6. LEGISLATIVE PROCESS FOR NUCLEAR LAW

The processes of drafting national legislation establishing or revising a legal framework for the development and use of nuclear technology and the use of nuclear material are not significantly different from the process of law making in any other field of national interest. Nuclear energy legislation, like any other legislation, must comply with the constitutional and institutional requirements of each State's political and legal system. However, the subject of nuclear energy is highly complex and technical, with some activities and materials posing unusual risks to human health, safety and the environment, and also national and international security risks. As a result, an extremely detailed and complex body of technical elements has been elaborated to ensure that nuclear related activities can be conducted in a safe, secure and environmentally acceptable manner. These technical elements comprise general principles, mandatory requirements or rules, non-binding guidelines or recommendations and informal practices. They cover a wide variety of technical areas, from nuclear power generation to the use of sealed radioactive sources in medicine, industry and agriculture. In addition, a growing structure of international treaty obligations and accepted rules of 'best practice' has been developed, providing opportunities for governments to harmonize their State's laws with the laws of other States, thereby contributing to the more efficient and consistent handling of matters of concern to the global community. Faced with a broad spectrum of technical rules, how should the legislator approach the task of making them binding on the entities involved in the uses of nuclear energy, including individual persons, private commercial enterprises, academic institutions, professional organizations and governmental bodies? It is clearly undesirable, if not impossible, to incorporate even a small number of them into national law. Doing so would result in extremely long texts, unintelligible to most persons. Also, it might hamper safety related progress by imposing inflexible constraints on the application of useful advances in science, technology, management and regulation. In addition, technical rules do not always have general applicability (even in the nuclear field); they may apply only to a specific activity or facility, with adjustments based on its particular characteristics and risks. As a matter of good practice in drafting legislation, laws should normally be framed in such a manner as to reflect generally applicable requirements covering a broad area of public interest. Technical rules need to be assessed in order to determine whether they are of general importance or whether they focus on particular types of activities or facilities. The first category of technical rules should be codified in laws of general applicability. The second category of requirements is more appropriately dealt with at a lower level in the national legal hierarchy. This approach has the advantage of giving competent authorities the flexibility necessary in order to revise requirements in response to new developments without amending the law. The lower level technical rules may be made effective in a number of ways. For example, some States may prefer to adopt them as administrative directives requiring the competent governmental authority to apply them to persons engaged in relevant nuclear related activities, while other States may prefer to adopt them as non-binding guidelines or recommendations developed by private expert bodies. Also, specific technical rules can be made binding on persons or organizations using nuclear energy by making compliance with them a condition for receiving permission in the form of a licence, permit or other type of authorization. In summary, the technical measures for safety, security and environmental protection in the nuclear field should take the form of: (a) Basic principles adopted as generally applicable law and binding on all persons and organizations; (b) Technical requirements (including regulations, guidelines and recommendations) that are not generally applicable and are made binding on specific persons or organizations by the regulatory authority or through specific licence conditions, binding only on the licence holder.

5.6.1. Assessment of nuclear programmes and plans

Whether a State is creating a framework for nuclear legislation or revising an existing framework, or merely updating one aspect of its nuclear legislation, the first step in the process should be an assessment of current and expected programmes and plans involving the use of nuclear techniques and material. Some States conduct activities across the full spectrum of nuclear technology applications, including nuclear power generation. Others only use radiation sources in medicine, agriculture and industry. Still others only engage in the mining of uranium or thorium for export. Some States have decided not to make use of certain nuclear technologies, but need to establish legal arrangements for the possible transit of nuclear material or other radiation sources through their territories. Finally, some States are concerned about possible nuclear related activities in neighbouring States that may warrant cooperative arrangements or emergency planning for radiological events. Whichever body is charged with conducting the assessment (whether a governmental body, a legislative committee or an independent panel of experts), the body should go beyond current and expected programmes and consider programmes that could emerge at some time in a rapidly changing global economy. It is always better to provide advance legislative guidance on how a particular area of nuclear related activity should be regulated (even if the guidance has to be revised later) than to leave that area without any regulatory requirements. Totally unregulated nuclear related activities, even if conducted in good faith, may raise health, safety, environmental or economic problems. Imposing rules after damage has been done or liabilities incurred is a very unsatisfactory approach. To the extent practicable, therefore, drafters of legislation should make the national regulatory arrangements for the conduct of nuclear related activities broad in scope. Furthermore, it is not sufficient merely to assess alternatives or options that might be of interest. Governments must be prepared to make firm decisions on the scope and character of the type of nuclear energy development that they wish to support. Such decisions require a clear expression of national policy, something that may involve protracted debate and the adjustment of views. Some activities may generate considerable political involvement, while others may be totally non-controversial. A State's policy regarding nuclear energy development can take a variety of forms; however, three approaches are typical. First, a government may actively affirm the desirability of the broadest exploitation of nuclear material and techniques by adopting a 'promotional' policy involving, for example, support for research and development, financial assistance, and the streamlining of administrative and regulatory procedures. A second, contrasting approach is the discouragement or even the preclusion of nuclear energy development through legislative prohibitions, the withholding of financial resources for nuclear related projects and the imposition of burdensome administrative and regulatory requirements. Most States have adopted an approach somewhere between these two extremes. This neutral approach relies primarily on business judgements arrived at by private commercial entities and on the normal regulatory process. Each government, through its own legal policy making processes, will determine which of these approaches, or which variation of one of them, best meets the State's interests.

5.6.2. Assessment of laws and the regulatory framework

As a complement to the assessment of current and expected programmes mentioned above, new nuclear legislation would do well to include a comprehensive assessment of the status of all laws and regulatory arrangements relevant to nuclear energy. This task may not be a straightforward one. In most national legal systems, many provisions not specifically directed towards nuclear related activities can have an important bearing on how such activities are conducted. In addition to general environmental laws, legislation concerning economic matters (e.g. taxation, liability, regulatory fees, monetary penalties and the setting of electricity rates), worker health and safety, criminal enforcement, land use planning, international trade and customs, scientific research, and many other areas, may impinge on enterprises engaged in nuclear related activities. Furthermore, most States already have some laws applicable to nuclear energy and regulatory bodies that deal with nuclear matters. If a conscientious assessment determines that these laws and bodies are adequate for regulating the State's current and planned nuclear related activities, there should be no reason to alter them. Of the many issues to be examined in an assessment of a State's nuclear law, the following are the most important:

(a) Does the current legislation make it clear that public health, safety, security and the environment are overriding considerations in the use of nuclear techniques and material?

(b) Are there major gaps or overlaps in the legal structure regarding the treatment of nuclear related activities or material, both those currently being conducted or used and those that can reasonably be expected?

(c) Have the most important terms used in the legislation been given clear and consistent definitions in the statutory documents? Does the use of different terms and definitions, or a failure to define certain terms, produce confusion about how nuclear related activities are to be regulated?

(d) Are the institutional responsibilities for regulating nuclear related activities clear and consistent, permitting efficient regulation without delays and bureaucratic conflicts?

(e) Does the present regulatory system involve unnecessary financial or administrative burdens on regulated entities or regulatory agencies that could be reduced in order to improve efficiency?

(f) Does the present system fully comply with the State's international legal obligations and reflect international best practice, as described in safety standards documents (such as the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (the Basic Safety Standards) [1]) promulgated by the IAEA or other relevant multinational bodies? Without an assessment covering at least the issues above, an effort to draft new or revise current legislation involves a real risk of making a State's nuclear legislation more confusing, inefficient and less effective.

5.6.3. Input from stakeholders

A very important step in the development of nuclear legislation is to obtain a clear perspective on how a new or revised regulatory law could affect persons and institutions having an interest in the nuclear field (stakeholders). Perhaps equally important, it is necessary to understand how stakeholders believe they will be affected. In the nuclear field, perceptions may well be as important as reality. Owing to the differing views on who has a genuine interest in a particular nuclear related activity, no authoritative definition of stakeholder has yet been offered, and no definition is likely to be accepted by all parties. However, stakeholders have typically included the following: the regulated industry or professionals; scientific bodies; governmental agencies (local, regional and national) whose responsibilities arguably cover nuclear energy; the media; the public (individuals, community groups and interest groups); and other States (especially neighbouring States that have entered into agreements providing for an exchange of information concerning possible trans boundary impacts, or States involved in the export or import of certain technologies or material). Stakeholder input can be obtained in various ways and at various stages of the legislative process. Depending on the culture and practices in a particular State, it is often wise to involve stakeholders early and at each stage of the process. For example, stakeholder input can be sought in making the assessments of programmes and laws discussed above. Also, in many States stakeholders have a right to provide input at some stage. Input can be in the form of written submissions or presentations to governmental agencies, legislative committees or special commissions, regardless of the entities making the assessment. Sometimes it is useful to prepare a document to which stakeholders can react to; such a document helps focus comments, which otherwise might range widely over subjects of marginal relevance. However, comments made in response to a general request for views can be valuable, even if they require a greater review effort by the entities making the assessment.

5.6.4. Initial legislative drafting

Having reviewed the assessment results and any preliminary stakeholder input, the responsible party (whether a governmental body, a legislative committee or an independent panel of experts) will be in a position to prepare an initial draft of legislation. An important issue at the outset is whether the legislation will cover all aspects of nuclear energy, or whether it will cover different aspects in a number of separate laws. Other fields of law are bound to be affected by comprehensive regulation. There is no uniform approach to this issue. Some States opt for a comprehensive Nuclear Energy Act, complemented by a set of regulations. Other States prefer to enact separate laws for the various fields to be covered, which also need to be complemented by regulations. When considering this issue, legislators need to take into account national legal traditions. In States with a tradition of comprehensive regulation, for example, legislators may prefer to incorporate the nuclear legislation into, for example, the existing environmental protection legislation. The manner in which States organize their nuclear legislation is not of overriding importance. What is important, however, is that the legislation is transparent, and clearly understandable, with easy access to relevant provisions both for stakeholders and the general public. This argues against the piecemeal addition of provisions to laws and regulations covering related fields. If, for example, the licensing procedures for nuclear power plants, for research reactors and for other nuclear facilities are set out as amendments to different laws, the objectives of transparency, clarity and easy access cannot be achieved. Given these considerations, many States have found it convenient to adopt a single comprehensive nuclear law covering all the subjects. The comprehensive law approach does not mean that certain nuclear related matters not central to nuclear safety may not be handled in separate legislation. If certain subjects (e.g. worker protection or waste disposal) are effectively and consistently treated under separate legislation, it would not be either necessary or efficient to include these matters in specific nuclear legislation. Special regulations on taxation should be inserted into a general tax law, criminal law provisions should be part of a criminal code and mining regulations should be part of a general mining law. A number of States split the areas to be covered by nuclear legislation into two major parts, the first dealing with the prevention of accidents and incidents through, for example, licensing and control mechanisms, and the second dealing with nuclear liability. This two part approach is certainly reasonable, although there is the minor drawback that the two parts may lose their mutual consistency if they are amended at different times. Safeguards and export and import control provisions may also warrant special legislation for insertion into foreign trade legislation, as they differ substantially from the safety and liability provisions of nuclear legislation.

One structure for a comprehensive nuclear law that may provide useful guidance is:

(a) Title of law.

(b) Table of contents:

I: Objectives of the law;

II: Scope of the law;

III: Definitions of key terms;

IV: The regulatory authority;

V: Authorizations (licences, permits, etc.);

VI: Responsibilities of licensees, operators, users;

VII: Inspection;

VIII: Enforcement.

(c) Section IX to X: specific requirements (for each subject area, for example radiation protection, radioactive material and radiation sources, the safety of nuclear installations, emergency preparedness and response, mining and milling, transport, radioactive waste and spent fuel, nuclear liability and coverage, safeguards, export and import controls, and physical protection).

(d) Section X: final clauses (amendment, repeals of earlier laws, etc.).

The drafters of an initial legislative proposal should:

(a) Identify the key terms that require precise definition in a separate section;

(b) Clearly assign institutional responsibility for each regulated activity, in order to avoid confusion;

(c) Ensure that the legislative language is sufficiently clear about which activities are covered and which procedures must be followed in order to comply with the law;

(d) Ensure that the legislation contains clear provisions for dealing with disagreements and with violations of regulations (e.g. conflicts of jurisdiction between agencies, appeals by operators against regulatory decisions and the punishment of wilful violators of regulations);

(e) Ensure that the legislation makes it clear how the financial costs of various activities will be met (e.g. through general tax revenues, licence fees or financial penalties for violations);

(f) Ensure that the legislation provides for adequate involvement in the regulatory process of stakeholders (including local communities and, where trans boundary issues may arise with neighbouring States);

(g) Ensure that the legislation contains provisions giving regulators the flexibility necessary in order to adjust to technological, social and economic changes;

(h) Ensure that the legislation contains provisions for the orderly implementation of new or revised arrangements (e.g. a delay period before entry into force or phasing in over an extended period);

(i) Ensure that the legislation contains provisions for the treatment of activities being carried out and facilities being operated in accordance with earlier standards (e.g. the exemption of certain activities and facilities from certain requirements (grandfathering)).

There may be other equally important things that the drafters of an initial legislation proposal should do. The Secretariat of the IAEA is prepared, upon request, to conduct reviews of the draft nuclear legislation of Member States and to make suggestions for improving it (on a confidential basis, if so desired). Such reviews focus on whether the draft is consistent with relevant international legal instruments and with international best practice, as reflected in relevant IAEA safety standards. The IAEA's Secretariat is also ready to provide samples that have been adopted in various States and which provide an adequate legal framework for the regulation of nuclear energy.

5.6.5. First review of the initial draft

After the preparation of a reasonably detailed initial draft, many governments have found it useful to subject the draft to a review, in order to assess its adequacy and public acceptability.

Here again, some form of stakeholder input can be useful, for example comments made in writing within a specified period or statements made at hearings conducted by a governmental agency or a legislative body

5.6.6. Further legislative consideration

At this stage, national constitutional practice normally dictates how the legislative proposal will be handled; only a few points are emphasized here. Throughout the legislative process, which may be long and complex, relevant expertise in nuclear technology and nuclear law needs to be available to the drafters of legislation. It is not always self-evident that terms having a precise special meaning within the nuclear energy community should be preferred to terms more familiar to the layperson (or vice versa). Efforts to make legislation less complex and more user friendly are to be applauded. However, changes in nuclear terminology can lead to uncertainty on how an activity is to be regulated. Also, drafters of legislation who are not nuclear energy specialists must consider the scientific validity and practicability of suggestions that other persons may make with a view to enhancing nuclear safety. Nuclear technology has proponents and opponents who hold strong views. Drafters of legislation need to bear in mind how proposed ‘improvements’ will affect nuclear energy development and to seek balance and objectivity.

5.6.7. Legislative oversight

Too often, after a difficult and contentious effort to enact nuclear legislation has been concluded, the legislative body moves on to other matters and fails to monitor the practical impact of its law making. Many States have established mechanisms for helping determine whether a law is being implemented in a manner consistent with its objectives. Regulatory authorities and the users of nuclear energy must, of course, be given a reasonable opportunity to conduct their activities without disruptive interference. However, legislation containing reasonable provisions for reporting on implementation can help to maintain confidence in the regulatory process. Annual reports by regulatory authorities are a common mechanism in this regard, and it may be useful for the legislature to specify which matters should be covered in such reports.

5.6.8. Relationship to non-nuclear laws

When nuclear legislation is being drafted, legislators must consider the impact that national legal requirements in non-nuclear fields may have on achieving the objectives of the legislation. Those national legal requirements may derive from an enormous range of laws. In the case of nuclear installations, for example, a minimum list of related laws could well include laws relating to:

(a) Local land use controls;

(b) Environmental matters (e.g. air and water quality and wildlife protection);

(c) The economic regulation of electric power utilities;

(d) The occupational health and safety of workers;

(e) General administrative procedures of governmental bodies;

(f) Transport;

(g) The export and import of nuclear material;

(h) Intellectual property rights;

(i) Liability for non-nuclear damage;

(j) Emergency management;

(k) Taxation.

A thorough understanding of relationships is necessary, of course, in order to avoid conflicts and confusion in the application of laws. Another aspect, however, is the avoidance of duplication in the handling of issues within the national legal framework. If an issue is being handled adequately and if the existing legislation can be expected to deal effectively and efficiently with issues that may arise out of planned nuclear related activities, separate nuclear legislation is not needed. Legislative restraint may sometimes be as appropriate as legislative activism in the case of nuclear related activities.

5.6.9. Reflecting international conventions or treaties in national legislation

As noted above, a large number of international instruments (e.g. conventions and treaties) have been developed to cover specific nuclear related subjects. Adherence to these instruments has both an external and an internal aspect. As a matter of international law, States that take the necessary steps under their national laws to approve (or ratify) such an instrument are then bound by the obligations arising out of that instrument in their relations with other States Parties (assuming that the instrument has entered into force). In addition, such States need to establish legal arrangements for implementing those obligations internally. There are two basic approaches to internal implementation. Most States require that the provisions of international instruments be adopted as separate national law. This approach is reflected in Article 4 of the Convention on Nuclear Safety [2], which states that: "Each Contracting Party shall take, within the framework of its national law, the legislative, regulatory and administrative measures and other steps necessary to implement its obligations under this Convention." It normally involves, first, the translation of the international instrument into the national language and, second, the organization of key provisions in a manner consistent with the national legal framework. This makes the obligations easier to implement internally. The second approach to internal implementation does not require the second step. The constitutional arrangements in some States make international agreements concluded in a manner consistent with national law a part of those States' legal frameworks, without further legislative action; the international instruments are deemed to be 'self-executing'. Even in such cases, however, it is important to translate the agreement into the national language and to publish the resulting text in the relevant compilation of national legal instruments, so as to give all affected Parties adequate notice of the requirements of the international instrument. Some international instruments contain provisions that are not intended to be internationally binding. However, States may wish those provisions to be internally binding. In such cases, a State will need to adopt them as laws through its normal legislative procedures

5.6.10. Incorporating international guidance documents or foreign law provisions into national legislation

For drafters of legislation unfamiliar with nuclear law and nuclear technology, a tempting approach in preparing national nuclear legislation is merely to incorporate into it the language of safety standards or guidelines developed by international organizations (primarily the IAEA) or the text of laws adopted by States with highly developed legal frameworks. This approach is tempting for a number of reasons. First, it reduces the amount of totally new legal texts that must be drafted. Second, it takes advantage of the technical or legal expertise of experienced organizations or States. Third, in the case of the incorporation of IAEA safety standards, it can help a State receive IAEA technical assistance to comply with the requirements of the IAEA. However, these advantages are accompanied by difficulties that warrant careful consideration. One difficulty concerns whether and how international or foreign requirements will fit into a State's legal structure. In some States, constitutional provisions prohibit the incorporation of external requirements (and even of references to them) into national law, particularly if those requirements have not been translated into the national language. Moreover, if a State's constitution permits incorporation, either directly or by reference, questions of application may nevertheless arise. For example, standards or guidelines prepared elsewhere may contain provisions that are inconsistent with or contradictory to important features of a State's legal structure. It is often difficult to identify the inconsistencies or contradictions without a thorough understanding of their implications, something that may not be evident to a drafter of legislation with only a limited background in nuclear matters. Another question that may arise is that of translation. Foreign terms relating to nuclear energy that are not translated may be meaningless or confusing to persons expected to apply the national law or to comply with it. Therefore, even if external requirements are considered to be a good basis for a State's own requirements, experience suggests that they should be translated into the national language. A second difficulty is that the documents containing external requirements may not be readily available, either to the national regulatory authorities or to licence applicants and licensees. For this reason, if it is decided to incorporate external requirements, they should be reproduced in a convenient form. A third difficulty arises from the fact that the external requirements (e.g. international instruments) may be subject to change, sometimes on a regular basis. If they are changed, a State that has incorporated them into its national legislation faces the problem of how the changes, which may have been made without its participation, are to be handled. In many States, revising a national law can be a lengthy and laborious process. Furthermore, regulatory authorities and licensees cannot be expected to comply with changes they have not been informed about. There are a number of methods for dealing with requirements derived from international or foreign sources. A common method is the adoption of legislation creating the basis for rules and regulations in the relevant area and authorizing the regulatory authority to adopt external requirements as binding rules or regulations. A second method (often used for requirements relating to quantities or activity levels of radioactive material) is to spell out the requirements in technical appendices or annexes to the law. If this is authorized in the legislation, these technical appendices or annexes can then be revised through an administrative procedure that does not require amendment of the law. A third method would be for the national law to authorize the regulatory authority to apply external requirements directly as licence conditions binding on a licensee.

5.7 International Legal Regime

The work of the International Atomic Energy Agency (IAEA) involves many treaties, which play an important role in establishing legally binding international rules in the areas that they cover. The treaties relating to the work of the IAEA cover a wide range of subjects, from the organization of the IAEA's own work to nuclear safety, nuclear security, safeguards and nuclear non-proliferation, and civil liability for nuclear damage.

Treaties under IAEA's auspices include the Convention on Nuclear Safety, the Convention on the Physical Protection of Nuclear Material and its amendment as well as a number of conventions on civil liability for nuclear damage.

5.7.1 Convention on Nuclear Safety (CNS)

The Convention on Nuclear Safety (CNS) aims to commit Contracting Parties operating land-based civil nuclear power plants to maintain a high level of safety by establishing fundamental safety principles to which States would subscribe. The Convention is based on the Parties' common interest to achieve higher levels of safety that will be developed and promoted through regular meetings. It obliges Parties to submit reports on the implementation of their obligations for "peer review" at meetings that are normally held at IAEA Headquarters. This mechanism is the main innovative and dynamic element of the Convention.

5.7.2 Convention on the Physical Protection of Nuclear Material (CPPNM)

The *Convention on the Physical Protection of Nuclear Material* was signed at Vienna and at New York on 3 March 1980. The Convention is the only international legally binding undertaking in the area of physical protection of nuclear material. It establishes measures related to the prevention, detection and punishment of offenses relating to nuclear material.

A Diplomatic Conference in July 2005 was convened to amend the Convention and strengthen its provisions. The amended Convention makes it legally binding for States Parties to protect nuclear facilities and material in peaceful domestic use, storage as well as transport. It also provides for expanded cooperation between and among States regarding rapid measures to locate and recover stolen or smuggled nuclear material, mitigate any radiological consequences of sabotage, and prevent and combat related offences.

5.7.3 Vienna Convention on Civil Liability for Nuclear Damage

The IAEA serves as depositary for several international legal instruments on civil liability for nuclear damage, which aim to ensure compensation is available for damage, including transboundary damage, caused by a nuclear incident at a nuclear installation or in the course of transport of nuclear material to or from an installation. These include the Vienna Convention on Civil Liability for Nuclear Damage and the Protocol to amend it, the Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention and the Convention on Supplementary Compensation for Nuclear Damage.

The Vienna Convention on Civil Liability for Nuclear Damage aims at harmonizing the national law of the Contracting Parties by establishing some minimum standards to provide financial protection against damage resulting from certain peaceful uses of nuclear energy

5.7.4 Convention on Supplementary Compensation

The Convention on Supplementary Compensation (CSC) aims at establishing a minimum national compensation amount and at further increasing the amount of compensation through public funds to be made available by the Contracting Parties should the national amount be insufficient to compensate the damage caused by a nuclear incident.

5.7.5 Treaty on Non Proliferation of Nuclear Weapons (NPT)

The NPT aims to prevent the spread of nuclear weapons and weapons technology, to foster the peaceful uses of nuclear energy, and to further the goal of disarmament. The Treaty establishes a safeguards system under the responsibility of the IAEA, which also plays a central role under the Treaty in areas of technology transfer for peaceful purposes

5.7.6 Convention on Early Notification of a Nuclear Accident

The Convention on Early Notification of a Nuclear Accident, adopted in 1986 following the Chernobyl nuclear plant accident, establishes a notification system for nuclear accidents from which a release of radioactive material occurs or is likely to occur and which has resulted or may result in an international transboundary release that could be of radiological safety significance for another State. It requires States to report the accident's time, location, nature, and other data essential for assessing the situation. Notification is to be made to affected States directly or through the IAEA, and to the IAEA itself.

5.7.7 Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency

The Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, adopted in 1986 following the Chernobyl nuclear plant accident, sets out an international framework for co-operation among States Parties and with the IAEA to facilitate prompt assistance and support in the event of nuclear accidents or radiological emergencies. It requires States to notify the IAEA of their available experts, equipment, and materials for providing assistance. In case of a request, each State Party decides whether it can render the requested assistance as well as its scope and terms.

Ghana has already adhered to the following international legal instruments adopted under the auspices of the IAEA:

(a) Convention on Early Notification of a Nuclear Accident (INFCIRC/335);

(b) Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (INFCIRC/336);

(c) Convention on Nuclear Safety (INFCIRC/449);

(d) Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the ‘Joint Convention’), INFCIRC/546;

(e) Convention on the Physical Protection of Nuclear Material (INFCIRC/274) and Amendment thereto (INFCIRC/274/Rev.1/Mod.1); and

(f) Convention on Supplementary Compensation for Nuclear Damage (INFCIRC/567);

Ghana has also concluded a Comprehensive Safeguards Agreement (INFCIRC/226) and an Additional Protocol (INFCIRC/226/Add.2) with the IAEA.

5.8 Nuclear Industry Regulatory Regime

5.9 Emergency Preparedness and Incident Management

Nuclear and radiological emergencies and accidents may have a detrimental impact not only on the facilities in which they occur but also on the environment in the vicinity. Under certain circumstances, radioactivity may be transported by air or water to areas beyond the facility and may even cause long distance pollution, including pollution within the territories of other States. This risk scenario applies especially to nuclear power plants and facilities with a similar risk potential, but it also may apply to the transport of nuclear material if, owing, for example, to a traffic accident, there is a release of radioactivity into the air or into water. Radioactive sources may also cause accidents. An accident with a radioactive source may be described as an event that leads to the loss of normal control over the source and which could entail the radiation exposure of individuals and the environment. The consequences may be trivial or serious and requiring an emergency response. Consequently, there must be a system in place designed to reduce the risk of emergencies and to mitigate their consequences. Such a system should provide the means necessary for dealing with the on-site and off-site effects of an emergency. Organizing emergency response at the international level requires co-operation with the competent bodies of other States. There has to exist an organizational and legal framework that makes possible and facilitates the establishment and implementation of emergency plans. There also have to be available trained staff, technical equipment and financial resources. Emergency planning and preparedness are required for all human activities. It follows that in all States there already exist general organizational structures to deal with emergencies. Entities that carry out potentially hazardous activities are under a legal obligation to organize in-house emergency preparedness. State organizations like fire brigades step in if in-house measures cannot cope with the emergency. Special nuclear and radiological emergency planning may, as appropriate, be based on existing emergency organizations, which will probably need to be complemented by the provisions necessary for their specific purpose. The obligation of the State to deal with emergencies derives from the State's overall duty to protect its citizens and residents against harm. The obligation of the licensee to organize emergency planning and preparedness is part of its prime responsibility for nuclear and radiation safety.

5.4.1 GOALS AND ELEMENTS

On-site emergency preparedness comprises all measures necessary for detecting reliably and in a timely manner incidents likely to create an emergency, for keeping them under control and for bringing them to an end with as little damage done as possible. In the case of reactors, the main goal is to prevent core damage, to maintain or restore the cooling of the core and to bring the plant to a safe state. Mitigating measures may be necessary in order to avoid a serious radiation impact on the plant site and the environment. This applies to all nuclear facilities and nuclear and radiation activities. Off-site emergency preparedness is aimed at minimizing the radiation exposure of the public and the environment. Basic elements are information exchange and assessment of the information available. It is especially important that on-site information be passed to off-site bodies, and vice versa. In the event of a release of radioactivity, information about the time of the release and the characterization of the activity released (the source term) is indispensable for decision making. In the event of a significant release of radioactivity to the environment, special measures to protect the population may be necessary, for example traffic control and limitation, appeals to the population to stay indoors, the evacuation of the population, the distribution of iodine tablets and the organization of immediate health care, including decontamination. On-site and off-site emergency preparedness should be considered at all stages of the licensing procedure, and especially during the design and construction of facilities and radiation equipment in order to make possible and facilitate countermeasures.

5.4.2 IMPLEMENTATION OF EMERGENCY PREPAREDNESS

5.4.2.1 Legal framework

On-site and off-site emergency preparedness must be addressed in nuclear legislation. With regard to the emergency measures to be prepared for by the licensee, there are two legal approaches that may be adopted alternatively or cumulatively: legislators may, in the nuclear legislation, expressly make it the duty of the person responsible for the specific activity (the licensee) to organize and carry out the emergency response; and emergency preparedness can be made a prerequisite for the granting of a licence. In the licensing procedures, the respective concepts designed for the activity in question may be developed and established. Emergency planning by State or local authorities also needs a legal framework. It may be necessary to amend and supplement existing legal provisions for emergencies, but existing structures and organizations should be maintained and the existing experience should be applied. The law should provide for a single authority responsible for emergency response, including the notification of other entities. The authority should be the point of contact at which all information is collected and distributed. Overlapping or gaps between the competences of State and local authorities should be avoided. This is especially true for federal States, where conflicts may arise between the central government and the regional government. The legal framework should authorize the competent entities, in accordance with the constitution, to take measures that may interfere with the rights of persons, especially in the vicinity of an emergency. Countermeasures may require the evacuation of people and perhaps the enforcement of evacuation. There may have to be restrictions on the freedom of movement of people and on the use of or trade in contaminated food or animal feed. State emergency response is not meant to replace the licensee’s duty to react to emergencies, but is meant to supplement it if the licensee’s resources are insufficient. The law should clearly define the fields to be covered by the licensee and those to be covered by State authorities. Responsibilities should be allocated in a way that excludes ambiguity. There is one situation in which the State or local authorities have the prime responsibility for emergency preparedness, namely in the event that radioactive sources are not under the control of the person responsible for them but, for example, are lost or abandoned or in the State illicitly. As such sources may be discovered unexpectedly and in places far away from well-equipped emergency response teams, the legal framework should ensure that the local police, fire-fighting or other services are trained and equipped to assess the situation provisionally and cope with it until special radiological emergency response teams arrive. In order to respond to the trans boundary consequences of a nuclear or radiological emergency, States should conclude appropriate arrangements with neighbouring States. Even States without programmes involving nuclear energy and radioactivity should conclude such arrangements in order to be able to cope with emergencies originating from neighbouring States.

5.4.2.2 Emergency plans

The principal means of ensuring adequate emergency preparedness and response is to establish and maintain on-site and off-site emergency plans. The Convention on Nuclear Safety and the Joint Convention both require the Contracting Parties to take appropriate steps to ensure that they have in place on-site and off-site emergency plans that cover the actions to be taken in the event of an emergency. The plans should be tested before the nuclear installation goes into operation and subsequently be subjected to tests on a routine basis. Each Contracting Party is required to take appropriate steps to ensure that, insofar as it is likely to be affected by a radiological emergency at one of its nuclear installations, its own population and the competent authorities of the States in the vicinity of the nuclear installation be provided with appropriate information for emergency planning and response. Contracting Parties that do not have nuclear installations on their territories should also prepare emergency plans if they are likely to be affected by emergencies occurring in neighbouring States. As required by Basic Safety Standards, competent authorities should ensure that:

(a) Emergency plans be prepared and approved for any facility, activity, practice or source that could give rise to a need for emergency intervention;
(b) Emergency intervention organizations be involved in the preparation of emergency plans, as appropriate;
(c) Emergency plans take into account the results of any accident analyses and any lessons learned from operating experience and from accidents that have occurred in connection with similar activities;
(d) Emergency plans be periodically reviewed and updated;
(e) Provision be made for training personnel involved in implementing emergency plans and that the plans be tested at suitable intervals;
(f) Prior information be provided to members of the public who could reasonably be expected to be affected by an accident.

Emergency plans should:

(a) Allocate responsibilities for notifying the relevant authorities and for initiating intervention;
(b) Identify operating and other conditions that could lead to a need for intervention;
(c) Specify intervention levels for protective actions and the scope of their application, with account taken of the possible degrees of severity of emergencies that could occur;
(d) Lay down procedures, including communication arrangements, for contacting emergency intervention organizations and for obtaining assistance from fire-fighting, medical, police and other services;
(e) Describe the methodology and instrumentation for assessing the accident and its consequences on and off the site;
(f) Describe the public information arrangements in the event of an accident;
(g) State the criteria for terminating each protective action.

Among the most important elements in emergency response is the early availability of the information necessary for evaluating the risk and choosing the right countermeasures. Procedures, including communication arrangements for contacting emergency intervention organizations and for obtaining assistance from various services, are therefore of particular importance. There should be a constantly updated list of relevant addresses with telephone and fax numbers and e-mail addresses. In general, on-site emergency plans are implemented by the licensee, while the implementation of off-site emergency plans and of any trans-boundary emergency plan is the responsibility of State or local authorities.

5.4.3 INTERNATIONAL CO-OPERATION

5.4.3.1 Obligations under public international law and relevant conventions

Close co-operation with neighbouring States is essential for an effective regime for dealing with the consequences of a radiological accident. It is a generally accepted principle of public international law that States that permit potentially hazardous activities within their territories must ensure that these activities do not have significant detrimental effects on the territories of other States. As a consequence of this principle, States are obliged to mitigate detrimental effects on the territories of other States and to pay compensation for damage suffered. One may conclude from this legal situation that States are obliged to offer to co-operate with an affected State in jointly organizing emergency response arrangements. The obligations with regard to trans boundary emergency planning are established by the Convention on Nuclear Safety and the Joint Convention Moreover, the Assistance Convention and the Early Notification Convention are international instruments designed to establish a basis for international emergency response that takes into account the lessons learned from the Chernobyl accident. The Contracting Parties to the Early Notification Convention undertake to provide exact information in order to facilitate the organization of countermeasures. Accordingly, most Contracting Parties have made known to the IAEA and to other Contracting Parties their competent authorities and the points of contact responsible for providing and receiving the information to be provided under this convention. The points of contact, and a corresponding focal point within the IAEA's Secretariat, are required to be permanently accessible. The Early Notification Convention, which provides only a general framework, suggests that, where deemed appropriate, States should consider concluding bilateral or multilateral arrangements to establish detailed legal frameworks for the trans boundary exchange of information on accidents. The Assistance Convention is also a framework agreement, designed to establish a general basis for mutual assistance in the event of a nuclear accident or radiological emergency. A Contracting Party may call for assistance from any other Contracting Party, from the IAEA or from other international intergovernmental organizations. Contracting Parties are required to identify and notify the IAEA about experts, equipment and materials that they could make available for the provision of assistance to other Contracting Parties in the event of a nuclear accident or radiological emergency. They are also required to make known to the IAEA, and to one another, their competent authorities and points of contact authorized to make and receive requests for and to accept offers of assistance.

5.4.3.2 The IAEA's ENATOM

In 1989, in order to facilitate the practical implementation of the Early Notification Convention and the Assistance Convention through co-ordination of the measures taken by States pursuant to them, the IAEA issued an Emergency Notification and Assistance Technical Operations

Manual (ENATOM, latest edition effective as of 1 December 2002) [10]. ENATOM provides guidelines for IAEA Member States Parties to the two conventions, for relevant international organizations and for other States regarding the development of mechanisms for co-operation with the IAEA within the framework of the conventions. In addition, it describes the IAEA's role in the regime established by the two conventions and the desired interaction between the IAEA and the States involved. Legislators may wish to build upon the ENATOM concept when establishing a legal framework for emergency preparedness and response. ENATOM describes the objectives of the IAEA emergency response system as derived from the IAEA's statutory responsibilities and from the functions assigned to the IAEA in the two conventions. It underlines the importance of contact points at the national level and at the IAEA. In order to ensure the rapid exchange of clear information, an emergency classification has been developed, which is spelled out in ENATOM. For events inside nuclear facilities, three classes of emergency have been defined: Alert, Site Area Emergency and General Emergency. Events below the level of Alert are not considered to be emergencies; they are classified as unusual events, which may be reported but do not trigger response actions. For events outside nuclear facilities, four classes of emergency have been defined: Radiological Accident, Missing Source, Satellite Re-entry and Elevated Radiation Levels. If an event belonging to the first three classes constitutes a trans boundary emergency of radiological significance, States Parties to the Early Notification Convention are required to notify the IAEA Emergency Response Centre. The IAEA is prepared to send, immediately upon request, qualified personnel to requesting States for the purpose of helping to assess the radiation situation and for making recommendations.

5.10 Fundamentals of Nuclear Security, Safety and Safeguard

5.11 Localization