Determination of Shielding Thickness for a Nuclear Reactor By Monte Carlo Simulations Using Random Number Generators

A dissertation submitted in partial fulfillment of the requirement for the award of the degree of

MASTER OF TECHNOLOGY

In

NUCLEAR SCIENCE AND ENGINEERING

By

NALIN

(2K15/NSE/04)

Under the Guidance of

Dr. NITIN K. PURI

Assistant Professor

DEPARTMENT OF APPLIED PHYSICS

DELHI TECHNOLOGICAL UNIVERSITY

BAWANA ROAD, DELHI – 110042

JULY - 2017

दिल्ली प्रोद्योगिकी विश्वविद्यालय
DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)

CERTIFICATE

This is to certify that the dissertation entitled on **"Determination of Shielding Thickness for a Nuclear Reactor By Monte Carlo Simulations Using Random Number Generators"** submitted to Delhi Technological University (formerly Delhi College of Engineering) by **NALIN (2K15/NSE/04)** in the partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Nuclear Science and Engineering (Applied Physics Department)** is a bona fide record of the candidate's own work carried out under the supervision of **Dr. Nitin K. Puri**. The information and data enclosed in this thesis is original and has not been submitted elsewhere for honoring any other degree.

Signature of the Candidate

Signature of the Supervisor

Dr. Nitin K. Puri
(Assistant Professor)
Applied Physics Department
Delhi Technological University
Delhi - 110042

Signature of the HOD

Prof. S. C. Sharma
(Head of Department)
Applied Physics Department
Delhi Technological University
Delhi - 110042

Candidate Declaration

I hereby declare that the work which is being presented in this thesis entitled **"Determination of Shielding Thickness for a Nuclear Reactor By Monte Carlo Simulations Using Random Number Generators"** is my own work carried out under the guidance of **Dr. Nitin K. Puri**, Assistant Professor, Department of Applied Physics, Delhi Technological University, Delhi.

I further declare that the matter embodied in this thesis has not been submitted for the award of any other degree or diploma.

Date: **NALIN**

Place: New Delhi **Roll No. 2K15/NSE/04**

Acknowledgements

I would like to convey my sincere acknowledgements to all those who were involved in completion of my project.

I wholeheartedly want to thank my guide, **Dr. Nitin K Puri**, Assistant Professor, Department of Applied Physics, Delhi technological University for his excellent mentorship and support. Without his persistent efforts and guidance this project would not had been accomplished.

Besides my Supervisor, I would like to express my deep gratitude and respect to **Prof. S. C. Sharma**, Head, Department of applied Physics, Delhi Technological University, Delhi for his encouragement, insightful comments and valuable suggestions during the course. Sincere thanks are extended to Department of Applied Physics, Delhi Technological University for providing the required facilities so that I can work voraciously, barring the time limit.

I express my gratitude to **Ms. Umang Sharma**, **Mr. Nishant Shankhwar** and **Mr. Kamal Arora** for their valuable suggestions and continuous help during Simulation. There are many people involved directly or indirectly in the completion of this project work. My sincere thanks goes to them.

Last but not the least I wholeheartedly thank my father **Mr. Harish Kumar**, my mother **Mrs. Kusum**, my brother **Mr. Kushagra** and friends for their constant moral and emotional support.

NALIN

M.TECH. NSE

2K15/NSE/04

INDEX

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Shielding is done in a nuclear reactor to stop the radiation effects which are caused by it. The radiation effects which are caused by it cannot be undone and have severe impact on our health as well as to the environment. Hence, firstly we measure the impact that the neutrons have and then we shield it through concrete. A concrete shield is used because it has the highest neutron absorption cross section as well as it can stop secondary gamma radiation. In this project, we have used Monte Carlo simulations to simulate the shielding of nuclear reactor using random number generators. Our results show that as the thickness of the shield increases the number of neutrons absorbed and reflected increases because higher number of collisions occur as the thickness increases. Also, the transmitted neutrons decreases as the thickness increases because less number of particles goes on without collision. Moreover, in this project we have also calculated the variation of average energy of the neutrons, which decreases as we increase the shield thickness.

Chapter 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In nuclear physics radiation which is caused by neutron is a kind of radiation hazard. Another, more serious hazard of neutron radiation, is that it excites the material with which it is interacting, the capacity of neutron radiation to cause radioactivity in various materials is experienced vastly, including the body tissues [1]. This happens because the neutrons are captured by the nuclei of atoms, which are transformed to another nuclide, generally a radionuclide protection from these radiation is needed which depends on radiation shielding. Neutrons have very high kinetic energy, as they have no charge they won't feel any external forces, so the radiation caused by this radiation is viewed as the most severe radiation to the entire body even when it is exposed to external radiation sources. In contrast to conventional ionizing radiation in light of photons or charged particles which are shielded easily, neutrons are repeatedly bounced and slowed down (absorbed) by lighter nuclei. Hydrogen and hydrogen-rich material is more effective in shielding of neutrons than iron nuclei. The light atoms serve to slow down the neutrons by elastic scattering so they would then be able to be absorbed by shielding material. In any case, gamma radiation is regularly created in such reactions, so extra shielding has to be given to absorb it. Extra care must be taken to nuclei's that undergo fission or neutron capture that causes radioactive decay of nuclei, generating secondary gamma rays.

In our project we have used concrete as a shielding material as it contains water and gravel which provides shielding to both neutrons as well as induced gamma rays. Concrete provides the more stable solution for shielding as it cheap, can serve for a longer duration and can achieve high density depending on the output power of a reactor.

1.2 STATEMENT OF THE PROBLEM

Radiation protection systems against neutrons that are released during nuclear reactor operations are essential to reduce the dose to the radiological workers and to common individuals as well [2]. This research mainly focuses on the shielding of nuclear reactors while varying the thickness of the shield and noticing the behaviour of the neutrons which have different energy range. We have used a code and run that code in MATLAB. This code is based on the Monte Carlo Simulations.

1.3 OBJECTIVE OF THE RESEARCH

The objective of the research is to develop a shielding thickness that will allow less neutrons that will pass through the shield. This is done in MATLAB using Monte Carlo simulation. This code is used to simulate the nuclear reactor simulation of shielding the neutrons and to investigate the optimal thickness of the shield.

1.4 HYPOTHESIS OF RESEARCH

The hypothesis is based on the fact that hydrogenous materials are best for moderating neutrons because they have the elastic scattering phenomenon which is dominant mechanism in moderating the fast neutrons which is explained in detail in later chapters. We have used concrete which have water as well as gravel which provides shielding to both neutrons as well as secondary gamma radiation. We believe that such shielding is promising and effective.

1.5 SIGNIFICANCE OF THIS RESEARCH

The significance of this project lies in developing the shielding system for different range of neutrons which includes *fast* and *thermal neutrons.* Furthermore this project implies the deeper view of the hydrogenous material used as moderators and to absorb the neutrons by concrete just by increasing the thickness of it. The proposed shielding systems can be used in particle accelerators, nuclear power plant, medical applications, nuclear submarines, and in industrial applications.

1.6 LIMITATION OF THE STUDY

Our project used the computer simulation using Monte Carlo simulations in MATLAB. Further experimentation is required to get the performance of the shielding system on laboratory scale.

Chapter 2

NUCLEAR BASICS

CHAPTER 2

NUCLEAR BASICS

The alpha-particle scattering experiment was conducted by Ernest Rutherford and his collaborators and suggested that an atom has a nucleus which consists of the positive charge and around it the electrons revolve [1]. The net charge of positive ions and electrons are equal so the atom is electrically neutral. Further investigations revealed that for a distance more than 10^{-14} m, the alpha particles interact with nucleus by Coulomb force. However when the distance between alpha particles and the nucleus becomes less than 10^{-14} m there shows some anomaly in the behaviour of the scattered alpha particles in terms of Coulomb force. This implements that there exists some force other than Coulomb force which is Nuclear force, acts at a distance less than 10^{-14} m. It designates that *nuclear force has a short range* and it also shows that the radius of nucleus is around 10^{-14} m [2].

The atom consists of **electrons**, **protons** and **neutrons.** The protons and neutrons together called nucleons are at the centre of atom called nucleus. The nucleus of atom is surrounded by empty space in which there are electrons.

The standard model of Elementary particles consists of ***Leptons*** and ***Hadrons.*** Leptons are the lightest particles which consists of weak nuclear force which consists of ***Electron***, ***Muon*** and ***Neutrino***. Hadrons are subject to strong nuclear force but they are not fundamental particles because they are made up of ***Quarks.*** Hadrons consists ***Mesons*** and ***Baryons.*** Baryons consists of many particles but all the particles decay into protons, so proton is the only stable baryon. There are many other particles like ***Antibaryons*** and ***Mesons*** which can be further classified. But for nuclear reactors we need to consider only **electrons, protons, neutrons, photons and neutrino.**

Photon and **Neutrino** have zero rest mass and zero charge. As we all know the fact that the particle can behave as a particle or as a wave, this is called duality in nature [2]. So photon is associated with electromagnetic waves. Whereas Neutrino occurs in decay of certain nuclei. Basically there are six types of neutrinos but we will consider only neutrinos and anti-neutrinos which take part in nuclear engineering.

2.1 CONSTITUENTS OF NUCLEUS

Let us consider the nucleus of a hydrogen atom which consists of just one proton, next is the deuteron nucleus which has mass of two protons and a unit positive charge [4]. We might imagine that the deuteron nucleus consists of two protons and one electron. But it is not true because for that to happen when an electron comes out of nucleus must have energy of around 20 Mev according to uncertainty principle. This can also be explained by spin integrals. According to Rutherford this can be explained if the nucleus could be made up of protons and a similar particle in mass and spin with zero charge. This particle is known as neutrons. So now the deuteron nucleus consists of one proton and one neutron each of these particles has a spin of ½ and the total spin quantum number can be 0 or 1. The neutron was experimentally discovered by James Chadwick in 1932.

According to James Chadwick experiment, it was suggested that the nucleus contained Z protons and (A-Z) neutrons which is the *proton-neutron theory*. Electrons are outside the nucleus which is normally equal to Z. However, nuclei emit positron and electron. It is explained that, *the electron does not pre-exist in the nucleus but it is formed just at the instant of emission caused by the transformation of a neutron into a proton ($n \rightarrow p + e^-$).* Similarly, the *positron emission* is due to the vice-versa process, i.e., when a proton transforms into a neutron ($p \rightarrow n + e^+$) [5]. Although proton and neutron are made up of quarks but we will consider them as elementary particle.

As protons and neutrons can be changed over into each other in the nucleus, they are viewed as two different states of a single heavy nuclear particle to which the name nucleon has been given. Contingent on the relative number of protons and neutrons, atomic nuclei are grouped into following classes [5].

- **Isotopes** – The nuclei of an atom having same atomic number Z but different mass number A. For example $_{92}U^{235}$, $_{92}U^{236}$, $_{92}U^{239}$.
- **Isobars** – The nuclei of an atom having the same mass number A but different atomic number Z. For example $_{11}Na^{22}$, $_{10}Ne^{22}$.
- **Isotones** – The nuclei having the same number of neutrons. For example $_{6}C^{13}$ and $_{7}N^{14}$ are isotones having same number of neutrons in their nucleus.
- **Isomers** – These are those nuclei in which internal structure is different but having the same Atomic Number Z, mass number A and neutrons N. Due to difference in structures their internal energies may be different which can be manifested by different decay periods in case of radioactive nuclei.

TABLE 2.1 Constituents of a nucleus ad their properties.

Particle	Relative Mass	Relative Charge	Charge/C	Mass/Kg
Proton	**1**	**+1**	**$+1.6\times10^{-19}$**	**1.67×10^{-27}**
Neutron	**1**	**Neutral**	**0**	**1.67×10^{-27}**
Electron	**0.0005**	**-1**	**-1.6×10^{-19}**	**9.11×0^{-31}**

2.1.1 NUCLEAR RADII

An approximation shows that the nucleus may be considered to be a sphere with a radius given by

$$R = 1.25\ f_m \times A^{1/3} \qquad \textbf{......(1)}$$

Where R is the radius of nuclei, f_m is in femtometers and A is atomic mass.

One femtometers i.e. 10^{-15} m.

As Volume V, is proportional to cube of the radius i.e.

$$V = \left(\frac{4}{3}\right)\pi R^3 \qquad \textbf{......(2)}$$

So from equation 1 and 2 we get to know that volume is proportional to atomic mass of the atom i.e A. One more thing can be concluded from the above equations that A/V ratio is constant for all nuclei. A/V ratio denotes nucleons per unit volume. By virtue of this we can understand that the nuclei have the same density whether they are small or large which is proposed in nuclear drop model.

2.1.2 BINDING ENERGY

Let us consider a nucleus containing N neutrons and Z protons. If we try to pull apart this nucleus into its individual neutrons and protons, a certain amount of work has to be done because these particles are tightly held together by strong attractive nuclear forces. In other words a definite amount of energy has to be supplied to break the nucleus into its constituents and move them to infinity with each constituent being at rest. This energy is referred to as ***binding energy*** of the nucleus [1]. The binding energy of the nucleus gives its stability, higher the binding energy more stable is the nucleus.

After the separation, if the nucleon gets merged to form a nucleus, their energy must be less than what it was when they were separated. Einstein mass-energy relation postulated that, the combined mass in the merged state must be less than the sum of their masses calculated individually when they are far away from each other [1]. This defect in mass is called ***mass defect***. Let us denote mass defect by Δm, the energy emitted is Δmc^2 which is the binding energy (BE).

$$BE = \Delta mc^2 \qquad ......(3)$$

Let M be the mass of nucleus $_zX^a$, M_n be the mass of neutron and M_p be the mass of proton.

Then the mass defect Δm is

$$\Delta m = NM_n + ZM_p - M \qquad ......(4)$$

And the binding energy of the nucleus is

$$BE = (NM_n + ZM_p - M)c^2 \qquad ......(5)$$

It is more convenient to consider mass of an atom as compared to nucleus because the calculations must be easier. So we add and subtract from equation (5) the mass of Z electrons.

$$BE = (NM_n + ZM_p + ZM_e - M - ZM_e)c^2 \qquad ......(6)$$

Now,

$$ZM_p + ZM_e = Z\,(M_p + M_e)$$

Where $(M_p + M_e)$ is the mass of one atom of hydrogen (M_H)

The binding energy of electron is negligible is negligible as compared to $(M_p+M_e)c^2$.

Similarly, $(M(_zX^a) + ZM_e)$ is the mass of atom $_zX^a$ (M_a).

Thus the binding energy in terms of masses of atom is

$$BE = (NM_n + ZM_H - M_a)c^2.$$

2.1.3 STABILITY OF NUCLEUS

The stability of a nucleus depends on the binding energy of a nucleus. The more the binding energy of the nucleus the more stable is the nuclei. In other words, if a nuclei does not gets converted into other nuclei on its own than it is a stable nuclei i.e. without the supply of energy from outside.

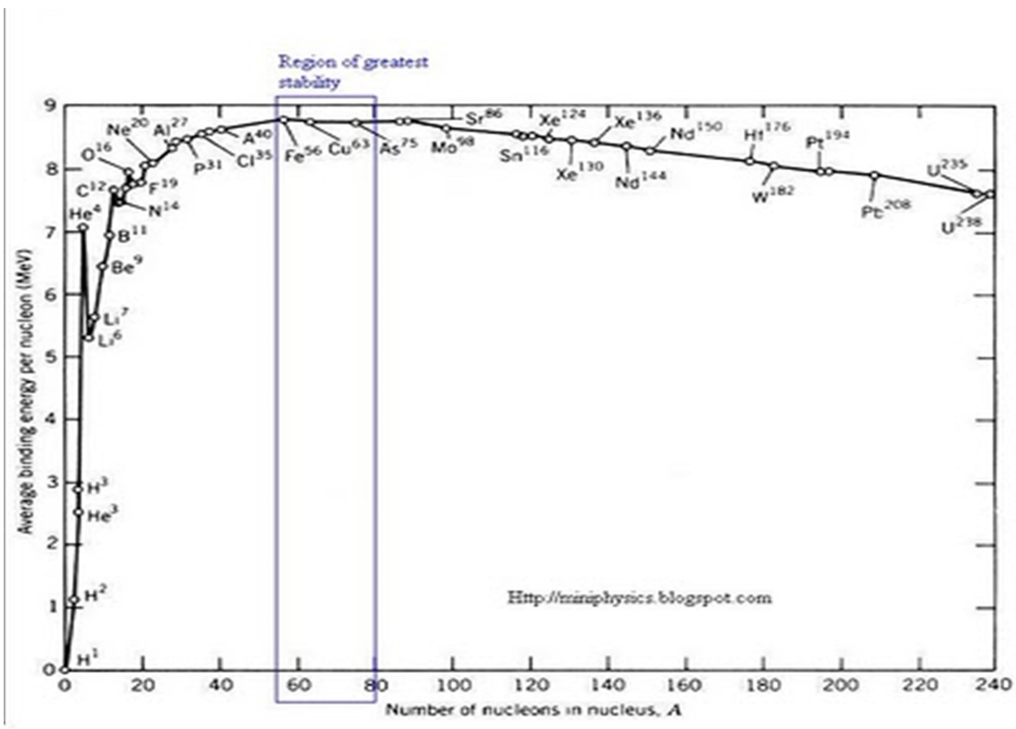

FIGURE 2.1 The binding energy curve.

- The average binding energy per nucleon is around 8 Mev, leaving out the lighter nuclei.

- The maximum binding energy per nucleon is happened to be around mass number 50. Fe(56) has the maximum binding energy per nucleon of around 8.8 Mev, which is the most stable nuclei.
- Nuclei having very high mass numbers and very low mass numbers tends to be least stable as they have the least binding energy per nucleon. The lower the binding energy per nucleon easier it is to isolate the nucleus constituents.
- Nuclei with low mass numbers can undergo nuclear fusion, where lighter nuclei are joined together under specific conditions so that the end product might have greater nuclear binding energy per nucleon.
- Nuclei with higher mass numbers may undergo nuclear fission, where the nucleus split into two daughter nuclei with the release of some neutrons. The daughter nuclei have more prominent binding energy per nucleon.

2.2 RADIOACTIVE DECAY

Now the question arises, what happens to the unstable nuclei?

The unstable nucleus moves towards stability by emitting certain radiations. Such nuclei are called radioactive nuclei or a radioisotope. The nuclei with $Z \geq 83$ are radioactive nuclei which are naturally occurring.

2.2.1 RADIOACTIVE DECAY LAW

Rutherford and Soddy concluded an experiment and based on that experiment have given some observations which formulated the following laws or called the laws of *Radioactive Disintegration*.

1. Radioactive decay is a spontaneous process independent of external conditions.
2. One nuclei decay at a particular instant.

3. Radioactive decay per unit time is directly proportional to the total number of nuclei in that substance.

Now the questions arise what are these radiations?

These radiations are:

Alpha decay – Helium nucleus is emitted.

Beta decay – Electrons are emitted.

Gamma decay – Photons are emitted.

We have discussed the shielding of these particles in chapter 3 in detail.

2.3 NUCLEAR REACTIONS

A ***nuclear reaction*** is a reaction in which two nuclei or nucleus interacts to produce two or more nuclear particles or ɣ rays. The characteristics of any nucleus can be changed by bombarding it with different energetic particles. Now consider the reaction,

$$a + X \rightarrow Y + b,$$

\`a' is a projectile which strikes \`X', which is a target nucleus.

\`b' is an outgoing particle and \`y' is a residual nucleus.

Or it can also be written as X(a, b)Y.

They can also be exothermic or endothermic just like in chemical reactions. Here Q value determines the reaction is endothermic or exothermic.

Conservation laws of nuclear reactions:

1. Conservation of charge.

2. Conservation of nucleons.
3. Conservation of energy.
4. Conservation of linear momentum.
5. Conservation of angular momentum.
6. Conservation of spin.
7. Conservation of isotopic spin.
8. Conservation of parity.

Magnetic dipole moment and electric quadruple moment are not conserved.

Types of nuclear reactions:

For energy generation there are basically two types of nuclear reactions which are ***Nuclear Fission*** and ***Nuclear Fusion***. Most of the reactors currently running operate under nuclear fission to generate electricity. But this reaction has to be controlled. Nuclear fusion reactor is still under research to generate electricity.

2.3.1 NUCLEAR FISSION

Nuclear fission was first discovered by Otto Hahn and Strassmann in 1939. Nuclear fission is a process in which the target nucleus gets hits by neutrons to produce two or more lighter nuclei with different atomic mass with a large amount of energy of the order of 200 Mev. For example when a thermal neutron strikes the uranium nucleus it gets absorbed in the nucleus which splits that nucleus into two lighter nuclei also called as daughter nuclei's.

$$_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{92}U^{236*} \rightarrow {}_{56}Ba^{144} + {}_{36}Kr^{89} + 3{}_{0}n^{1} + Q$$

Here Q is around 200 Mev.

We do not always get the same daughter nuclei but the daughter nuclei always have atomic mass lying in between 50 and 150.

This type of fission is called *induced fission*. Some fission does occur on their own which happens in heavy nucleus i.e with atomic mass greater than 220. These types of fissions are called *spontaneous fission*.

2.3.2 NUCLEAR FUSION

Nuclear fusion is a process in which two or more, lighter nuclei combine or fuse together to form a single stable heavy nuclei. For example

$${}_1H^2 + {}_1H^2 \rightarrow {}_2He^4 + Q$$

Here Q is the energy released in the process which is around 17.6 Mev [].

A lot of research is going on to harvest energy through controlled fusion reaction.

2.3.3 NUCLEAR CROSS-SECTION

It is the probability of a bombarding particle to interact with the target nucleus to carry out a nuclear reaction. In other words, it is the probability of quantitative measurement of nuclear reaction. Basically it is the area presented by the nucleus to the bombarding particle. The area in which the target nucleus gets hit by the incident particle will cause reactions whereas the particle which escapes this area does not cause reactions. So probability of reaction depends on cross-section directly.

The reaction cross section depends on the nature of interaction viz.

1. Energy of the particle.
2. Type of incident particle.
3. Target involved.

Let us denote cross section by σ

$$\sigma = \frac{N}{N_0 N_t}$$

Where N, is number of nuclei undergoing interaction per second

N_0 is the number of incident particles interacting per second per unit area

N_t is target nuclei per unit area.

If N_t is equal to 1 then it means that there is only one nuclei per second, then

$$\sigma = \frac{N}{N_0}$$

2.4 NEUTRON INTERACTIONS:

Compound Nucleus Formation:

First the target nucleus gets hit by the particles (generally neutron) and gets absorbed in it to form a compound nucleus. Secondly the compound nucleus gets decayed in a number of ways.

One of the main features of this compound nucleus formation is that their cross-sections have a maxima at certain incident neutron energies [1]. These maxima's are called *resonances*. These resonances are mandatory in cross sections to form the compound nucleus before the interaction takes place. This interaction can take place if the compound nucleus does exhibit in one of the excited states of the nuclei.

Now to remove a neutron from a nucleus we need separation energy, however this energy reappears when the neutron enters again into the nucleus. Therefore, it follows that when a neutron collides with a nucleus the compound nucleus is formed which is in an excited state. This compound nucleus is having energy equal to the kinetic energy of the incident neutron plus the binding energy of the neutron in the compound nucleus.

Elastic Scattering: In Elastic scattering when a neutron strikes the nucleus which is usually in its ground state interacts with nucleus and left the nucleus in its ground state. In this process the neutron reappears. The elastic scattering cross section can be defined in terms of the function of the energy of the incident neutrons which can be divided into three regions:

1. Low energy region – σ_e (potential scattering) is approximately constant. The scattering in this region is caused by the forces exerted by the target nucleus on the incident neutrons. It's cross section is

   $$\sigma_e \text{ (potential scattering)} = 4\pi R^2 \text{ ,where R is radius of nuclei}$$

2. Resonance region – this region happens after potential region which is due to formation of compound nucleus formation.
3. Smooth region – At higher energies the resonances overlap each other which becomes impossible to distinguish individual resonances. In this region σ_e is smooth and slowly varying function of energy.

For example,

$${}_{79}Au^{197} + {}_{2}He^{4} \rightarrow {}_{79}Au^{197} + {}_{2}He^{4}$$

In this reaction the direction of momentum changes and its velocity also changes.

Inelastic Scattering: In this process the nucleus gets excited by bombardment of neutrons and emits gamma rays. Rest of the process is same as that of Elastic Scattering. This is an endothermic reaction. This procedure does not happen unless the neutron has adequate energy to put the nuclei in its initial excited state. Accordingly, σ_i is zero up to some threshold energy. Generally, the energy at which the initial energized state is discovered shows reductions with increasing mass number. As a result, σ_i is nonzero over a bigger energy region for the heavier nuclei than for the lighter nuclei.

The threshold for inelastic scattering is 4.80 MeV for C, while it is just 44 keV for U^{238}. At energies well above threshold, σ_i is generally equivalent to σ_s. For example,

$$_3Li^7 + {}_1H^1 \rightarrow {}_3Li^{7*} + {}_1H^1$$

$$_3Li^7 \rightarrow {}_3Li^7 + \gamma$$

Charged Particle Interactions: When the neutrons interact with nucleus it may get absorbed by the nucleus. While in this process neutrons may get disappeared. This process can be endothermic or exothermic. This reaction produces proton or alpha particle as a byproduct. This kind of reactions occurs at a certain threshold not before it. Cross-sections of these particles are very small even for heavy nuclei's.

Radioactive Capture: In 99.9% of these reactions gamma rays are released. In this target nucleus will capture elementary particle from another compound nucleus of an excited state then release energy in the form of gamma rays. It is an exothermic reaction. It is convenient to measure the radioactive capture cross sections into three regions as it was done earlier in elastic scattering. In low energy region σ_γ varies at $1/\sqrt{E}$, where E denotes energy of neutron. Since E is directly proportional to v i.e neutron speed this means that σ_γ is inversely proportional to v. Therefore the low energy region is denoted by $1/v$ *region*. If we plot neutron cross-sections on a log-log scale the graph appears as a straight line with -1/2 as its slope. After $1/v$ region the region of resonances occurs at the same energies as the resonances in σ_s. Above the resonances region σ_γ drops rapidly and smoothly to very small values of about 1Kev in heavy nuclei and at higher energies in lighter nuclei.

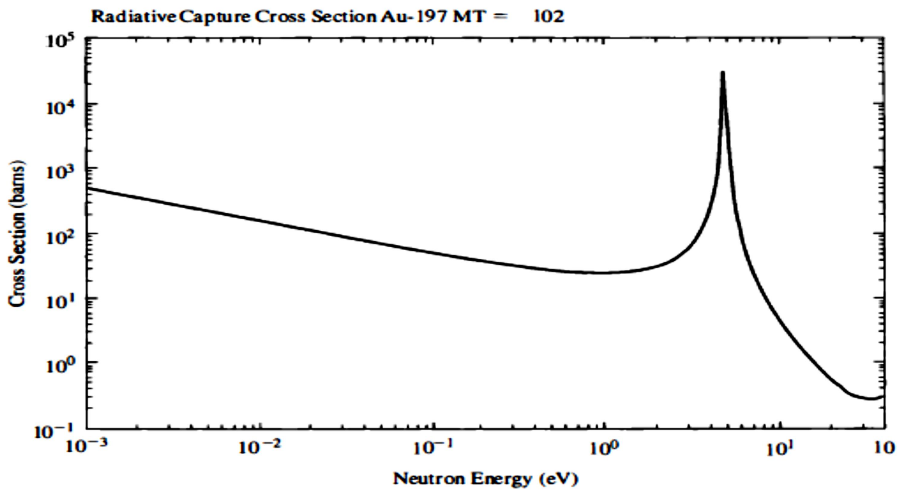

FIGURE 2.2 Radiative capture cross section of Au.

$$_{12}Mg^{26} + {}_{1}H^{1} \rightarrow {}_{13}Al^{27} + \gamma$$

$$_{6}C^{12} + {}_{1}H^{1} \rightarrow {}_{7}N^{13*} \rightarrow {}_{7}N^{13} + \gamma$$

2.4.1 TOTAL CROSS-SECTION:

It is denoted by σ_t which is the sum of all other cross-sections. σ_t varies with energy which reflects the variation of individual cross-sections. At low energies cross-sections varies as

$$\sigma_t = 4\pi R^2 + C/\sqrt{E}, \text{ where C is a constant.}$$

In the above equation the first term corresponds to the elastic scattering cross-section and the second term corresponds to radioactive capture or any other exothermic reaction possible at this energy [1]. If the first term is very much larger than the second term then σ_t is a constant at low energy. If the second term is larger than σ_t behaves in $1/v$ region of energy. In the resonances region, σ_t displays the resonances found in σ_s and σ_j, all of which happen at similar energies in each of these cross-sections. At higher energies over the resonances area, it turns into a smooth function of energy.

2.4.2 FISSION CROSS-SECTION

There are three different regions for σ_f, which are distinct in their cross-sections. In low energy region σ_f varies in the *1/v* region, which is then followed by the region of resonances, and finally it is followed by a smooth region or rolling region. It should be considered that σ_f is fairly large in *1/v* region.

2.4.3 NEUTRON ATTENUATION

Suppose we have taken a thick target of thickness X and a unidirectional beam of neutron having intensity I_0 is directed towards it. Now we place a detector behind the target in the same trajectory of the incident beam. When the particles get hit by the target it will collide and attain a different trajectory but the particles which did not collide will have the same trajectory and gets detected by the detector.

Let *I(x)* be the incident beam intensity that did not collide with the target after penetrating the distance x into the target. When the beam travels *dx* distance then the number of neutrons will decrease because they have collided with the target having an area 1cm^2 and a thickness *dx*. This decrease in intensity is given by

$$-dI(x) = N\sigma_t I(x)dx = \Sigma_t\, I(x)dx$$

By integrating with the help of the result

$$I\left(x\right) = I_0 e^{\Sigma_t x}$$

The intensity of the beam measured by the detector is

$$I\left(X\right) = I_0 e^{\Sigma_t X}$$

2.4.4 NEUTRON FLUX

Suppose a target is placed in between three incident mono-energetic beams of particles with different angles. Let them be I_1, I_2 and I_3. We have assumed that the interaction of the beam with the particles is independent of the angle with which they strike the target. The total interaction rate is given by

$$F = \Sigma_t(I_1 + I_2 + I_3)$$

As they are mono-energetic

$$F = \Sigma_t(n_1 + n_2 + n_3)v$$

Because (I = nv)

Where n = neutrons per cm^3 and v = speed of neutrons

$$F = \Sigma_t nv \qquad \text{......(h)}$$

Where $n = (n_1 + n_2 + n_3)$ because they are mono-energetic

The above equation is used in a reactor to find the number of collisions i.e `F' with neutrons having density of `n'.

$$\Phi = nv$$

Where Φ is *neutron flux.*

In terms of flux, the collision density is

$$F = \Sigma_t\, \Phi$$

Classification of neutrons on the basis of energy:

Cold neutrons – They have energy range less than 0.0003 ev.

Slow Neutrons (thermal) – They have energy range from 0.003 ev to 0.4 ev.

Slow neutrons (epithermal) – They have energy range from 0.4 ev to 100 ev.

Intermediate neutrons – They have energy range from 100 ev to 200 Kev.

Fast Neutrons - They have energy range from 200 Kev to 10 Mev.

Ultrafast neutrons - They have energy greater than 20 Mev.

Generally Neutrons which are formed in the fission reactions have energy range from 100 Kev to 15 Mev.

Out of which the most probable neutrons are having energy of 0.8 Mev and the average turns out to be 2.0 Mev.

The neutrons which are produced during fission have speed of 1.6×10^{7} m/sec.

These neutrons can be classified into two more categories i.e on the basis of fission neutrons which are:

1. Prompt neutrons consist of approximately 99% of the total neutrons and are released in 10^{-14} to 10^{-17} seconds.
2. Delayed Neutrons consist of only 1% and are released after 20 seconds. They are important in control of the nuclear reactors. They have utmost importance in time dependent behaviour of the chain reaction systems.

2.5 NUCLEAR FISSION CHAIN REACTION

A chain reaction is a self-propagating process in which number of neutrons keeps on multiplying rapidly almost in G.P during fission, till the whole material gets disintegrated. The neutrons which are produced during this reaction will cause fission of the fissile or fissionable nuclei and keeps on increasing. This is the reason we called it as a chain reaction.

These kinds of reaction can be defined quantitatively in terms of *multiplication factor*, which is denoted by ‘K.

$$K = \frac{Number\ of\ fissions\ in\ one\ generation}{number\ of\ fissions\ in\ preceeding\ generations},$$

K > 1 → Super-critical stage

K < 1 → Sub-critical stage

K = 1 Critical stage

In a nuclear weapon, uncontrolled nuclear reaction takes place and very large amount of energy is released. Devices which uses controlled nuclear chain reaction are called nuclear reactors. These reactions are controlled by varying the value of ‘K’.

2.5.1 CRITICAL SIZE

Critical size of the system containing fissile material is defined as the minimum size for which the number of neutrons produced in the fission process just balance those that lost by leakage and non-fission capture. The mass of the fissionable material at this size is called the critical mass.

Critical size for maintenance of chain reaction:

1. The fission of uranium nuclei which produces more neutrons then the number of neutrons used for inducing fission.
2. Non-fission capture of neutrons by the uranium and captured by the different substances in the system and their impurities.
3. Escape or leakage of neutrons through the surface of the system.

Neutrons generated + neutrons increase = neutrons absorbed + leakage neutrons

2.6 FOUR-FACTOR FORMULA

Consider a cycle starting with the fission of U^{235} nuclei by a thermal neutron. '*ν'* are *fast neutrons* which are emitted in this process. Out of these neutrons some neutrons are having enough threshold energy that can cause fission of U^{238} which can add more neutrons to the fast neutrons. Let the number of neutrons produced by U^{238} be denoted by 'ε'. So the total number of fast neutrons from fission has been increased from 'ν' to '$\nu\varepsilon$', where ε is called *fast fission factor* and is greater than 1. Now if we consider a finite size reactor core, some fast neutrons may get leaked before being slowed down to thermal energies. In accounting this, we introduced a factor l_f the *leakage factor* for fast neutrons. We should find out the total number of fast neutrons remained in the core to get slowed down which is $\nu\varepsilon(1-l_f)$. Moderator atoms are used to slow down these fast neutrons, but some of these fast neutrons are captured by U^{238} to form U^{239} which decays into $Np^{239}$and then finally to Pu^{239}, which happens particularly at the region of strong resonances. Now we should consider the *resonance escape probability,* 'ρ'. So out of $\nu\varepsilon(1-l_f)$ neutrons, a fraction of it $\nu\varepsilon(1-l_f)\rho$ escapes from being absorbed by U^{238}, while the fraction $\nu\varepsilon(1-l_f)(1-\rho)$ gets absorbed to get converted into pu^{239}. The neutrons which escaped are slowed to thermal energies. Some of these neutrons may get leaked from the core. To account for this we introduce l_{th} the *leakage factor for thermal neutrons*. The total number of thermal neutrons thermal neutrons present in the core is $\nu\varepsilon(1-l_f)\rho(1- l_{th})$. There is a factor called *thermal utilization factor 'f'*, which is a fraction of thermal neutrons absorbed by the fuel as compared to all the thermal neutrons absorptions in the whole assembly. The number of thermal neutrons that are actually absorbed by the fuel is $\nu\varepsilon(1-l_f)\rho(1- l_{th})f$.

If σ_a is the cross section of neutrons that are absorbed by the U^{235} and σ_f is the cross section of neutrons that are causing fission of U^{235}. Ultimately the number of second generation neutrons absorbed by fuel is $\nu\varepsilon(1-l_f)\rho(1- l_{th})f\ \sigma_f / \sigma_a$. This is known as *reproduction factor* or *multiplication factor* and is denoted by 'K', which is discussed earlier in chain reaction. If the reactor core size is very large, the leakage of fast as well as slow neutrons will be disregarded. Then the multiplication factor is then denoted by K_∞ and is given by

$K_\infty = \eta\varepsilon pf$, which is called four factor formula.

2.7 NUCLEAR REACTOR

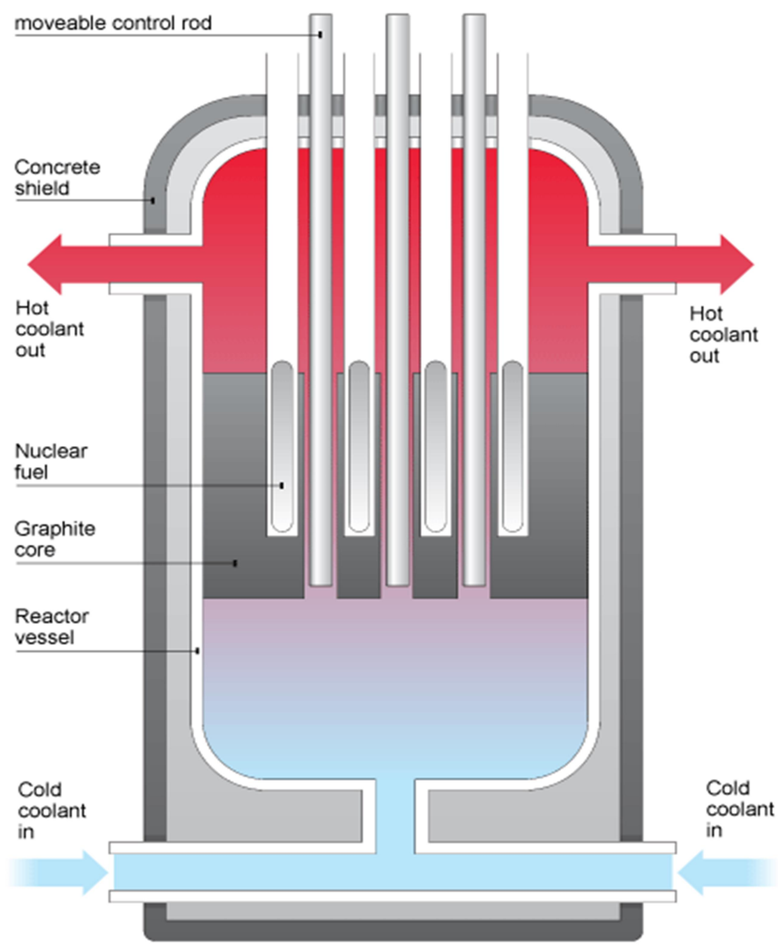

FIGURE 2.3 Schematic of a Nuclear Reactor.

Nuclear reactor is an apparatus in which nuclear fission is produced in the form of a self-sustaining chain reaction. It is an apparatus in which heat is produce due to nuclear fission chain reaction for the generation of electricity

The figure above shows the schematic diagram of the nuclear reactors. This is not an actual reactor but this is just showing the working of the reactors.

Core

This is the main part of the nuclear reactor. This is the region of the reactor where nuclear reactions take place. It consists of fuel, coolant, control rods, reflector and moderator, some reactors does not use moderator like in fast breeder reactors. Cores generally have different shapes and sizes but most preferred shapes are right circular cylinder having diameter from 0.5 to 15 meters.

Fuel

The Fuel is physically located in fuel elements which have uranium in the form of pure metal, a metallic alloy, or a ceramic. There are two kind of fuel

1. Fissile – Fissile material are those material which can start fission from thermal neutrons. There is no need to have energetic neutrons. It contains U^{235} but only has 0.0715% of natural uranium.
2. Fertile – Fertile material are those material which needs energetic neutrons to start fission. Once it starts then it releases fast neutrons and can get the fission chain reaction for the fertile material. It contains U^{238} nearly 99.3% of the natural uranium.

Control rods

It simply absorbs the neutrons so that it can either maintain or stop a reaction. It should have high neutron absorption cross section. It should not be radioactive and should have very high melting point. It is made up of Cd, B, Hf, Ir, Hg and rare earth metals. Control rods have moving mechanism so that they can get inserted into the core to decrease the neutron flux and make the 'K' approximately 1. If the 'K' value becomes less than 1 then the control rods are moved upwards so that the neutron flux increases inside the core. It is also used to shut down the reactor.

Moderator

Moderators are used to slow down the fast neutrons to thermal energies to undergo fission. Good moderators are basically consists of low mass numbers materials having small absorption cross section and large slowing down power. It should have high neutron scattering. For example: Water, D_2O, Graphite, Beryllium oxide and some organic compounds.

Reflector

It is placed round the core to reflect the neutrons back into the core. This is basically the thickness of the moderating material whose function can be understood in following ways. Suppose the core does not have reflector around it and is exposed to the air, so most of the neutrons gets escaped from the surface of the core to the environment, which is of no use. So to avoid it we use reflector around the core so that some of the neutrons gets reflected back into the core and can contribute to chain reaction. As the neutron economy increases the fuel required is also less.

Coolant

The reactor coolants are used to remove the excess heat from the reactor or from the other parts of the reactor where heat may be produced [7]. This heat is then passed onto the turbine to generate electricity. An ideal coolant must have very little effect on neutron. Following below are some properties of coolant.

1. Good thermal property
2. Should not absorb nor moderate neutrons
3. Should have high boiling point
4. Low melting point
5. Low power requirement for pumping
6. Chemically stable
7. Should not be toxic, explosive or flammable
8. Should not acquire intense long life radioactivity

Generally all nuclear reactors, except those operating at low powers can generate intense amount of neutrons and gamma rays. We will discuss the health hazards in the later chapter caused by neutrons and gamma rays. So to avoid this kind of radiation shielding is done. It is made up of concrete whose thickness depends on the output power of the reactor. This kind of shield which is protecting the persons who are near the reactor is called *biological shield*. Its thickness can vary from 6 feet to 8 feet [8]. Some materials are mixed into it to achieve the desired shielding.

There is another kind of shielding which is used to shield ɣ-rays. This kind of shield is placed just near the core so they do not interact with any other material [9]. But while doing so they also get heated up. So it needs to be cooled down, which is done by the coolant which is used in the reactor core. Generally we use stainless steel to shield ɣ-rays.

Classification of nuclear reactor:

1. Arrangement of fuel and moderator:
    a. Mixed with fuel and moderator
    b. Separated fuel and moderator
        i. Homogeneous fuel as solution mixed in moderator
        ii. Heterogeneous fuel in solid separated from moderator.
2. Energy of neutron causing fission
    a. Slow or thermal energy neutron
    b. Fast neutron/ fast reactor
    c. Intermediate neutron/ Epithermal neutron
3. Type of nuclear fuel
    a. U^{233} obtained from Th^{232}
    b. Pu^{238}obtained from U^{238}
    c. Natural occurring Uranium (99.28% U^{233} and 0.72% U^{235})
    d. Highly enriched Uranium (9.0% of U^{235})
    e. Slightly enriched Uranium (1-2% of U^{235})
4. Types of moderator
    a. Ordinary water (H_2O)
    b. Heavy water (D_2O)
    c. Graphite (Carbon) Moderator
    d. Beryllium Oxide (Low absorption cross-section of neutrons)
5. Method of heat removal
    a. Coolant only
    b. Fuel mixed with coolant
    c. Moderator coolant

d. Fuel moderator and coolant

6. Purpose of nuclear reactor

   a. Research

   b. Power Generation

   c. Isotope Production

   d. For production of Fissile material (Pu^{239})

   e. Propulsion of submarines and aircraft

2.8 CLASSIFICATION OF THERMAL POWER REACTORS

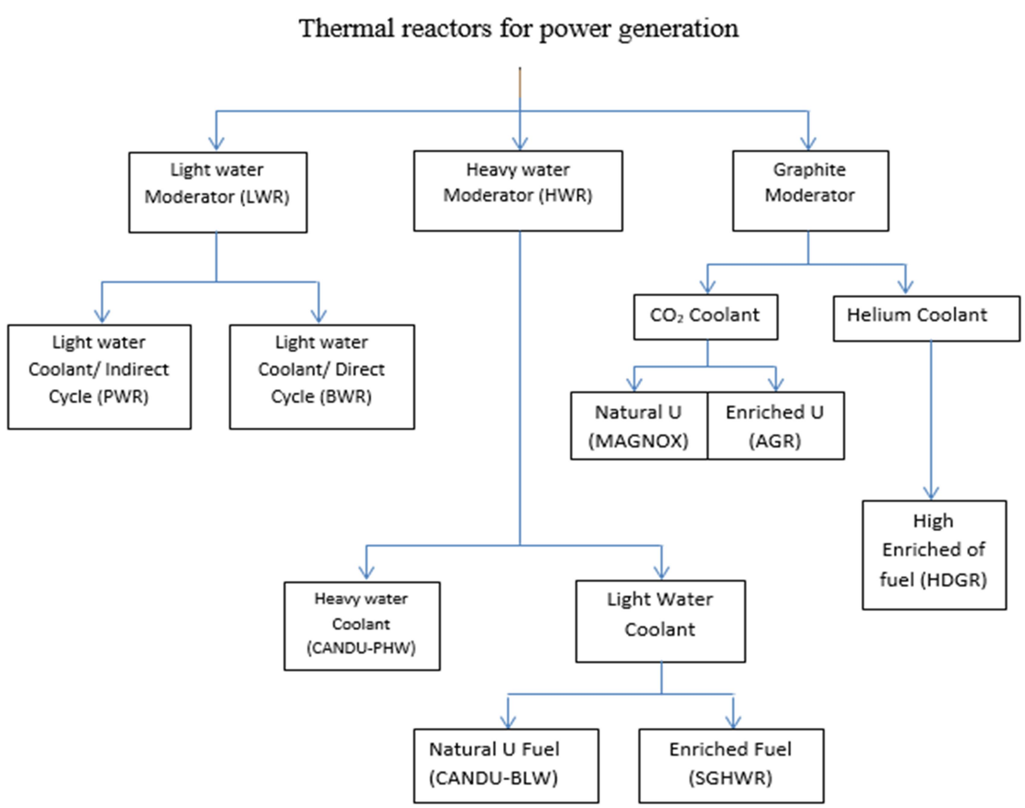

FIGURE 2.4 Classification of thermal reactors for power generation.

Chapter 3

RADIATION,

SHIELDING,

&

SIMULATION

CHAPTER 3

RADIATION, SHIELDING AND SIMULATION

3.1 RADIATION

The primary concern of our project is related to radiation caused by atomic or nuclear processes [10]. They can be classified into four general types as given below:

1) Charged particle radiation
   a) Heavy charged particles
   b) Fast electrons
2) Uncharged particles radiation
   a) Electromagnetic radiation
   b) Neutrons

Fast Electrons includes radiation caused by beta particles emitted in a nuclear decay process, as well as energetic electrons produced by any other process.

Heavy charged particles includes particles having atomic mass of 1 or greater than that are energetic ions such as alpha particles, protons or fission products from any other nuclear reactions.

The ***electromagnetic radiation*** includes radiation from X-rays which originates from the transition between electrons level inside the atom and nuclear transitions happening inside the nucleus.

Neutrons have no charge on them and they are generated in various nuclear processes so special care has to be taken to deal with this kind of radiation. They can be further divided into two sub-categories that are *fast neutrons* and *slow neutrons*.

In our project we will consider the neutrons having energy range from 1 ev to 8 Mev. We will plot different graphs to show the behaviour of neutrons respect to the thickness of the shields.

Radiation effects caused by *alpha particles* are not so pronounced when outside the body. It can be stopped by a single sheet of paper or from the dead skin cells present on our body [10]. But when they get inside our body by inhaling or by ingestion, then it can cause serious problems. As they are charged particles they get quickly reacted to the tissues and can cause serious injuries.

Beta particles can penetrate into the body more deeply than alpha particles but to penetrate beyond the skin they need to be energetic (1-5 Mev) [11]. When the beta particles get inside the body they strongly react and can cause hazardous effects. They can be stopped by lead but can lead to secondary radiation, so we use plastic to block beta particles.

ɣ-rays are blocked by high density material rather than low density material. Lead is particularly used for lessening the effect of ɣ- rays because of its high atomic number. As the atomic number of lead is high so are the protons and electrons, so the electrons that are large in numbers help in blocking the ɣ-rays. As the thickness is increased more is the stopping power for ɣ-rays.

Neutrons are uncharged so they can pass through dense materials without getting affected. Elements having low atomic number are preferred for shielding neutrons because they have higher probability of forming cross-sections that will interact with neutrons. Hydrogen and compounds having hydrogen are the best materials for attenuating neutrons and are inexpensive too. But low density materials do emit gamma rays when blocking neutrons. So to block neutrons we should use both low atomic and high atomic number elements.

3.2 RADIATION DOSE AND EXPOSURE

The radiation effects depend on the amount of it we are exposed. Therefore the amount of it we received are referred to as ***doses***, and the measurement of it is known as ***dosimetry***.

Absorbed dose (D) is a unit to measure the amount of energy deposited by radiation in 1 Kg of material. Its unit is ***grey***, abbreviated as ***Gy*** [7]. A person who have absorbed 1 grey of dose have absorbed 1 joule of energy in each Kg of body tissue. As this unit is too large to be accounted for so we use ***milligrey (mGy)*** or ***microgrey (μGy)***. It is just a physical unit that describes the effect of the incident radiation. It does not tell us anything about the biological effects of energy deposition on the tissue. It should be noted that 1 grey of alpha or neutron radiation is more harmful than 1 grey of gamma radiation.

Quality Factor

Different types of radiation have different quality factors based on their biological effects, for example fast neutrons have the 20 times more damaging properties then x-rays or gamma rays. So the fast neutrons have greater quality factor because they need less absorbed dose to produce the equivalent dose that are caused by more radiation doses by x-rays or gamma rays. The QUALITY FACTOR (Q) of a radiation type is defined as the ratio of the biological damage produced by the absorption of 1 Gy of that radiation to the biological damage produced by 1 Gy of X or gamma radiation [13].

3.2.1 EQUIVALENT DOSE

It is the measure of the biological effect of the dose which is the product of absorbed radiation dose and Q of the radiation delivering the dose.

In terms of specified biological damage an equivalent dose of one SIEVERT represents the quantity of radiation dose that is equivalent to one gray of X or gamma rays [12].

Sievert is the unit for equivalent dose. But in practice we use ***millisieverts*** (**mSv**) or ***microsievets*** **(µSv).**

3.2.2 DETERMINISTIC EFFECTS

Deterministic effects or Non-stochastic effects are those effects which do not occur below a threshold dose. These effects have a very clear relationship between exposure and the effects that are caused by it. In addition to this, the scale of effect is directly proportional to the amount of received dose. Deterministic effect occurs typically when the amount of radiation is too large for a small amount of time. Examples are:

- Erythema- shin reddening,
- Skin and tissue burns
- Cataract formation
- Sterility
- Radiation sickness and death

These effects can be categorized by their effect that is *acute* or *chronic*.

3.2.3 STOCHASTIC EFFECT

Stochastic effects are those effect that occurs only by chance and consists of mainly cancer and genetic effects. These effects arise only after few years of exposure. As the dose of these effects increases the probability of cancer or genetic effects also increases. Stochastic effects have no threshold dose which makes it harder to know that below how much radiation it is certain that the adverse effect does not happen. In addition to this, these effects can occur in individuals that have only been exposed to radiation below background levels. It can never be determined with certainty that the occurrence of the cancer or genetic effect was due to a specific radiation exposure. Its severity is not dose related. Stochastic effects include radiation carcinogenesis and hereditary effects.

3.3 SHIELDING

In radiation protection there are three ways to protect people from radiation exposure:

1. Limiting time – It is the time to which a person is exposed to the radiation directly. More the time more hazardous it is.
2. Distance – The amount of radiation exposure depends on the distance from the radiation source
3. Shielding – some radiation sources are so much intensive that the distance and time are not able to stop them. So to avoid that we need special care like shielding to block it. Radiation shielding is done by lead, concrete or water.

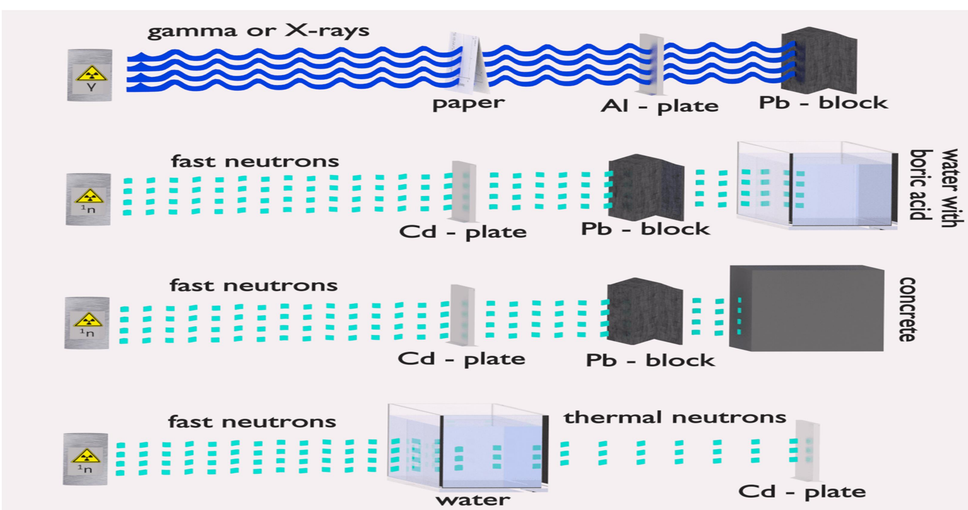

FIGURE 3.1 Types of material used for shielding different types of neutrons.

Our project deals with the shielding of neutrons, so to know it properly we should know how neutrons react with different material.

The principal of neutron shielding:

- Slow Down Neutrons – neutrons can be slowed down by a lighter element like hydrogen and hydrogen containing compounds like water, polyethylene or concrete. The nuclei of a hydrogen atom consist of a proton, which have the identical mass as of a neutron. Due to scattering a neutron transfers its energy to the hydrogen atom (even all of its kinetic energy gets transferred to the hydrogen nucleus). Let's take an example of billiard. Since a cue ball and another billiard ball have identical masses, the cue ball can be completely stopped and all its kinetic energy can be transferred to the billiard ball with the same velocity as it of the cue ball on the other hand when a ping pong ball gets hit to a bowling ball (neutron and a heavy nucleus) ping pong ball will get deflected with almost the same velocity. That is why lead is very inadequate for blocking neutron radiation, as neutrons are uncharged and can essentially go through thick materials.
- Absorb slow neutrons – Thermal neutrons are captured easily by the materials having high neutron capture cross-sections like boron, lithium and cadmium. Normally a very thin layer is sufficient to shield thermal neutrons. We use water to shield thermal neutrons.
- Shielding of the accompanying radiation – when we use cadmium as a shield the neutrons gets absorbed and will release gamma rays, which is secondary radiation. Therefore some additional shield is required to block the gamma radiation. This phenomenon does not occur with lithium or boron and when the compound boric acid is used in soluble form it serves a s great shielding material.

3.3.1 WATER AS A NEUTRON SHIELD

Water due to its high availability of hydrogen content is effective as a neutron shield. However due to low atomic number of hydrogen and oxygen it is not advisable to use water as a shield because it would not stop gamma radiation. So external shield is also used to shield gamma radiation or the thickness of the water shield can be increased to shield gamma radiation. Adding boric acid to the water can increase the absorption cross section of neutrons and can moderates the neutrons very effectively but can lead to another problem of corrosion.

3.3.2 CONCRETE AS A NEUTRON SHIELD

Most commonly used material in neutron shielding in nuclear power plant is concrete. Concrete also consists of hydrogen atoms but unlike water it has high density which can shield secondary gamma radiation as well and does not need any such maintenance. Concrete while making its composition can be changed and we can increase its density by varying the materials we put into concrete. Concrete can be divided into some categories which are as follows:

- Ordinary concrete – normal concrete with low density without any such additives.
- Heavy concrete – It uses heavy natural composites such as **Barites** (Barium Sulphate) or **Magnetite** or **manufactured aggregates** such as iron, steel balls, steel punch etc. It has higher density than normal concrete around (2300 Kg/m^3).
- Very heavy concrete – It can achieve density of around 5900 Kg/m^3 with iron as an additive, or it can achieve density of around 8900 Kg/m^3 with lead additives. Heavy concrete provides heavy neutron shielding as well as secondary shielding.

3.4 MONTE CARLO SIMULATIONS

Monte Carlo simulations are computerized mathematical analysis of a system that allows people to take into account for the risks in quantitative analysis and decision making processes [14]. Monte Carlo simulations uses risk analysis method by making up the models of possible results by substituting the various ranges of input values. It calculates result by calculating many times with different random numbers. Monte Carlo simulation could have tens of thousands of recalculations before delivering the exact result which depends on the number of inputs and the range specified for them. As we keep on increasing the number of calculations the desired result can be achieved by reducing the error. Monte Carlo simulation gives distribution of the values of the possible outcomes. A much more realistic approach is achieved by probability distribution function for describing uncertainty in variables of a risk analysis. During Monte Carlo simulations, from the input probability distributions values are sampled at random. Each and every set of samples is referred to as iteration, and the resulting output is recorded. In Monte Carlo simulations this process is repeated thousands of times and the result is shown as a probability distribution function of possible outcomes. In this way the Monte Carlo simulation provides a more comprehensive view of what may happen, what could happen and how likely it is to happen.

A Monte Carlo method may vary but it tends to follow a particular pattern which is:

1. Define a domain of possible inputs.
2. Generate the inputs randomly from a probability distribution over the domain.
3. Now perform a deterministic computation on the inputs.
4. Lastly aggregate the results.

A deterministic model means that one will get the same results for a particular set of inputs no matter how many times one re-calculates.

A Monte Carlo method uses random numbers and probability to solve complex problems.

We generally use this method for the models which are complex, non-linear and uses more than a couple of uncertain parameters [15]. We basically are converting deterministic model into a stochastic model by using random numbers as inputs, which involves probability of randomness.

In our project we have used Monte Carlo simulations, using random number, which are uniformly distributed. In a nuclear reactor, fast neutrons are emitted, so Monte Carlo simulation investigates the effectiveness of a shield which tends to absorb the neutrons. We have considered the reactor as a point source, and assigned its location as (0, 0, 0). A neutron which is emitted from the nuclear reactor has random initial direction, which has energy ranging from [E_{min}, E_{max}], with $1/\sqrt{E}$ distribution, which shows radiative capture in the low energy region. The shield has a wall of thickness 'THICK'. This thickness extends from 0 to THICK in the X-direction and extending infinitely in Y and Z-directions. Based on the neutrons energy, a distance 'D' is calculated, which measures how far the neutron travels through the shield before it has collided. Now based on the neutron direction the position is updated by D units. The neutrons which are seen on the right side of the shield is accounted as being *reflected* and if they are seen on the right side of the shield, it is accounted as being *absorbed*. Now if the neutron is inside the shield it is termed as *collided*. A neutron which has collided is either *absorbed* (end of the journey) or *scattered* which can travel in random directions and with a new lower energy. Every neutron is followed from origin to its final fate, which is reflection, transmission, or absorption. At the end we have calculated the summary which gives the number of neutrons with each fate and the average energy of each group of neutrons. In our project we have seen the variation of thickness and the particles which are absorbed, reflected and transmitted and the average energy of these neutrons.

Chapter 4

RESULTS

&

CONCLUSION

CHAPTER 4

RESULTS AND CONCLUSION

4.1 VARIATION OF NUMBER OF NEUTRONS WITH SHIELD THICKNESS

As we increase our shield thickness the number of neutrons that are being absorbed increases, which shows that more neutrons are being absorbed by the shielding material. The reflected neutrons also increases which shows that more neutrons are being reflected back into the reactor core. The transmitted neutrons are those neutrons which are not being shielded, so the number of neutrons keeps on decreasing as the shield thickness increases. The main purpose of shielding neutrons is that less number of neutrons gets transmitted through the shield and more number of neutrons gets reflected and absorbed by the shield. The neutrons which are absorbed by the shield are scattered and can have the tendency to either gets reflected back to the core or gets transmitted through the shield. Due to scattering the fast neutrons loses its energy to thermal neutrons which are easily shielded.

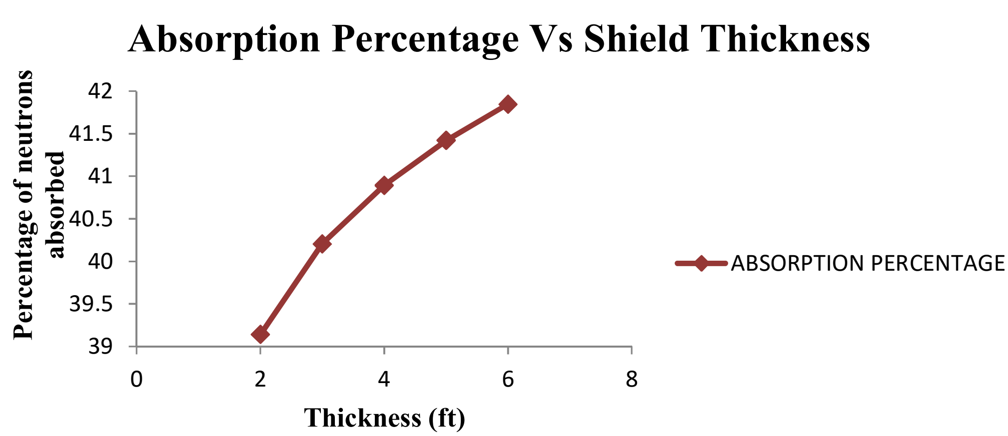

FIGURE 4.1 Absorption percentage Vs shield thickness

The absorption percentage increases with the shield thickness because as the hydrogen content in the concrete shield increases. The elastic scattering between the neutrons and the hydrogen atoms leads to increase in moderation of the neutrons which boosts the absorption cross section.

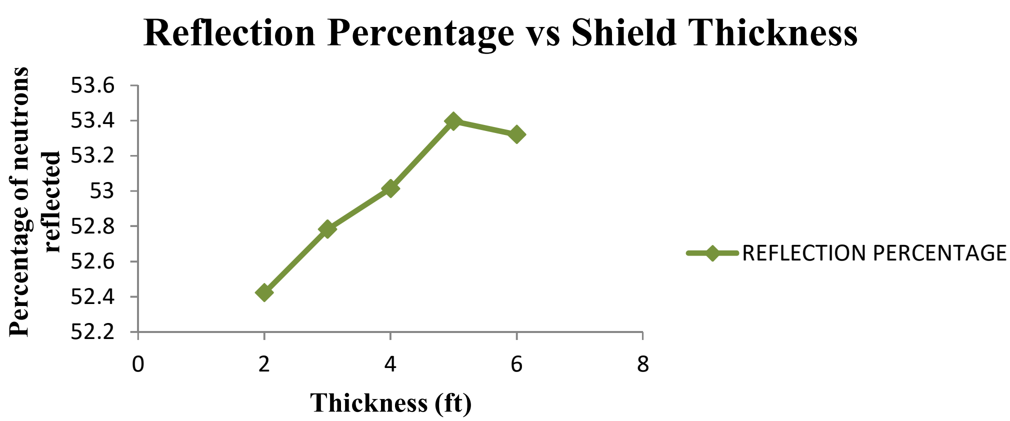

FIGURE 4.2 Reflection Percentage Vs Shield Thickness

Similarly the percentage of reflected neutrons also increases with the shield thickness. This shows that more neutrons are reflected back into the reactor core on increasing the shield thickness which is due to their elastic scattering with the hydrogen nuclei present in the concrete shield. The reflected neutrons have the highest probability which also improves neutron economy in the reactor core.

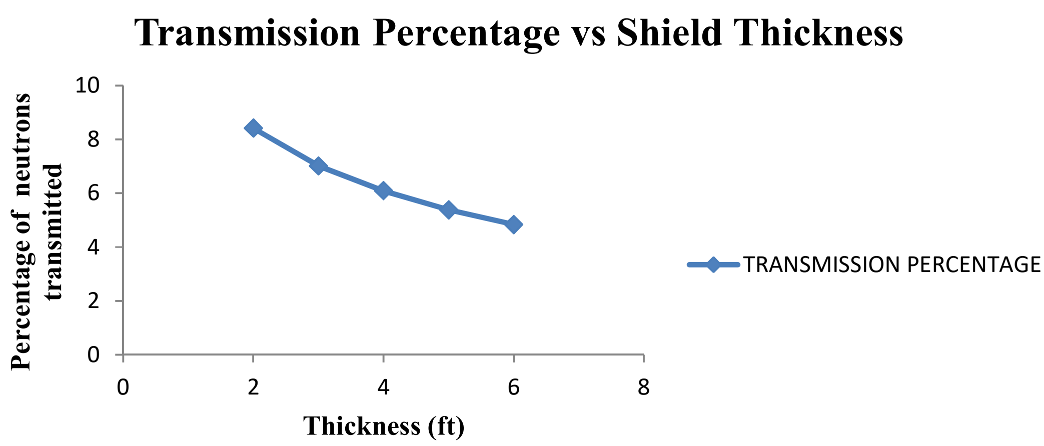

FIGURE 4.3 Transmission Percentage Vs Shield Thickness

The transmission percentage decreases as the shielding thickness increases because the probability of transmission of neutrons on being scattered after interaction with the hydrogen nuclei is very less. This can be attributed to the fact that higher hydrogen content in the concrete lets lesser number of neutrons being transmitted through the shield.

4.2 VARIATION OF AVERAGE ENERGY WITH SHIELD THICKNESS

Average energy is defined as ratio of the total energy of the neutrons to the total number of neutrons. The average energy decreases as the shield thickness increases because the energy of neutrons keeps on decreasing as we increase the thickness because of elastic scattering between the concrete matter and the neutrons. The energy of neutrons gets transmitted to the hydrogen atoms of the shield which will reduce the energy of the neutrons, and hence average energy decreases. On increasing the time which the neutron spends in the shielding material, they are slowed down to thermal energies. This increases the neutron absorption cross-section. The results below show the change in behaviour of average energy of absorbed, reflected and transmitted energy of neutrons with the shield thickness.

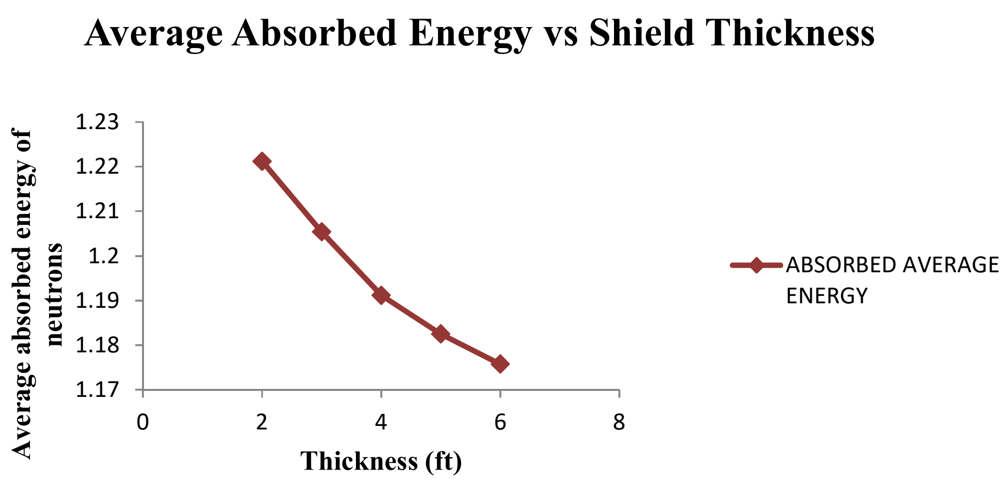

FIGURE 4.4 Average Absorbed Energy Vs Shield Thickness

The average absorbed energy is defined as the ratio of total energy of the absorbed neutrons to the number of neutrons absorbed by the shield. The average energy of absorbed neutrons keeps on decreasing with the shield thickness because on increasing the shield thickness, more number of neutrons interacts with the shielding matter and the rest are sent back to the core.

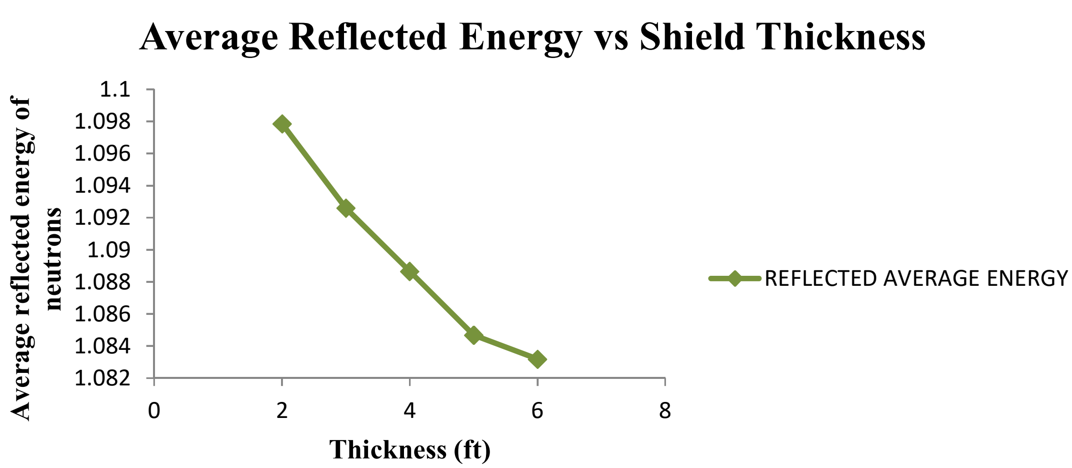

FIGURE 4.5 Average Reflected Energy Vs Shield Thickness

The average reflected energy is defined as the ratio of total energy of the reflected neutrons to the number of neutrons reflected by the shield. The average reflected energy is the least of all average energies because most of the neutrons get reflected back and their energy is also less as compared to absorbed and transmitted neutrons. This higher value of reflected neutrons accounts for this lower value. Also, increase in thickness increases the number of reflected neutrons which in turn decreases the average value of reflected energy with the thickness of shield.

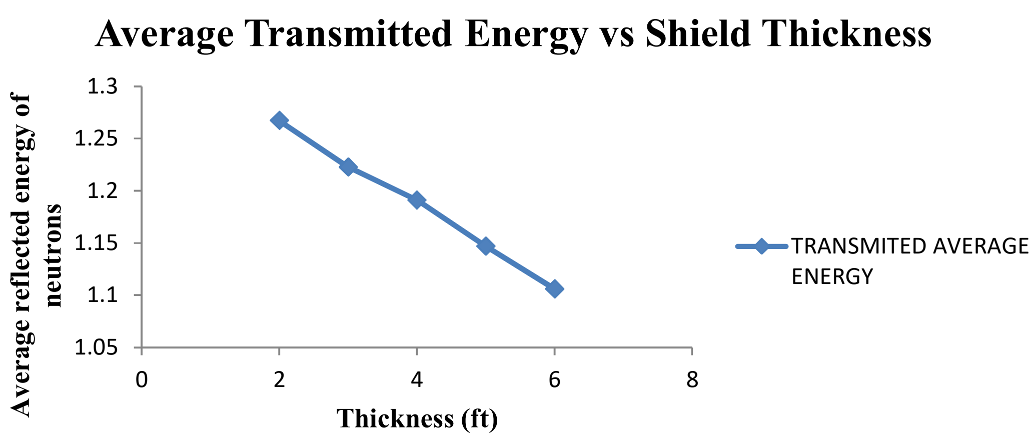

FIGURE 4.6 Average Transmitted Energy Vs Shield Thickness

The result above shows that average energy of the transmitted neutrons is the highest of all. The average transmitted energy is defined as the ratio of total energy of the transmitted neutrons to the number of neutrons transmitted through the shield. The main purpose of the shield is to block or minimize the transmission of neutrons and increase the reflection of neutrons back into the core. As the energy of the neutrons which are transmitted through the shield is large and the number of neutrons that are being transmitted is less so the average energy is greater for transmitted neutrons.

4.3 CONCLUSION

The conclusion of this project is that as we increase the shield thickness, the number of neutrons which are being reflected and absorbed increases. This is attributed to the fact that on increasing the thickness of the shield, more number of neutrons interacts with the hydrogen nuclei and are scattered or reflected back to the core which moderates them to slow neutrons that are easier to shield. The number of transmitted neutrons keeps on decreasing as we increase the shield thickness because there is a very little probability that they do not interact with the shielding material and pass through the concrete without any collision. Whereas the average energy of neutrons keeps on decreasing for absorbed, reflected and transmitted neutrons because the energy of the neutrons decreases because of elastic collision, i.e., higher number of collisions lowers the energy of the neutrons. On varying the thickness of the shield, we can improve the neutron economy in the nuclear reactor, and can protect the environment from the hazardous radiation.

4.4 FUTURE SCOPE OF THE PROJECT

This project shows how the variation of thickness can improve the shielding of neutrons. In the future, the following work can be carried out.

- Shielding of the gamma rays which are released by the absorption of neutron by the hydrogen nuclei.
- To study the effect of using a shield made up of a blend of different materials and also, the effect of using a number of layers of different material in making the shield.
- To study the radioactivity of the shielding material being induced due to the constant radiation by the neutrons and how to dump them.

REFERENCES

[1] Dose Standards and Methods for Protection against Radiation - NRC ... RSSC RADIATION PROTECTION 07/11.

[2] John R. Lamarsh and Anthiony J. Baratta, Introduction to nuclear engineering, Prentice hall, 2001.

[3] G.F. Knoll, Radiation Detection and Measurement - 3rd edition, John Wiley & Sons, Professor of Nuclear Engineering and Radiological Sciences- University of Michigan Ann Arbor, Michigan, 1999.

[4] Atomic energy Review, Vol. No. 2, June 1997.

[5] Radioisotopes and Radiation Methodology Medical Physics 4R06/6R03.

[6] G. R. Kelpin, Physics of Nuclear Kinetics, Addison-Wesley Publications Co., 1st edition, 1965.

[7] K. O. Ott, R. J. Neuhold, Introductory Nuclear Reactor Dynamics, American Nuclear Society, ISBN: 0-894-48029-4, 1985.

[8] W. M. Stacey, Nuclear Reactor Physics, John Wiley & Sons, ISBN: 0- 471-39127-1, 2001.

[9] N. Elsheikh, G. Viesti, I. ElAgib, F. Habbani, Journal Applied Radiation and Isotopes, 70 643–649, 2012.

[10] Radiation protection at CERN/Heinz Vinckel, D. ForkelWirth, S. Roesler, M. Silari, C. Thesis, Helmut Vinckel, DGSRP, CERN CAS, Bilbao, 1st June 2011.

[11] Sheikh M. U., Asim G.M.; "FARR's Shielding Calculations for Uprating", Report P1NSTKCH/NK1) 7, Islamabad, 1974.

[12] Price T, Horton C. C., and Spinny K. T., "Radiation Shielding", Pergamon Press Ltd., London, 1987.

[13] Strom Daniel J., “Ten Principles and Ten Commandments of Radiation Protection,” Health Physics, 70 (3):388-393, 1996.

[14]Fishman G. S., Monte carlo: Concepts, algorithms, and applications. N.Y., USA: Springer-Verlag, 1995.

[15] Codec for Reactor Computations, IAEA, Vienna, 1980.