Course Title: **Radiological Control Technician**
Module Title: **Physical Sciences**
Module Number: **1.04**

Objectives:

1.04.01 Define the following terms:

- a. Nucleon
- b. Nuclide
- c. Isotope.

1.04.02 Identify the basic principles of the mass-energy equivalence concept.

1.04.03 Define the following terms:

- a. Mass defect
- b. Binding energy
- c. Binding energy per nucleon.

1.04.04 Define the following terms:

- a. Fission
- b. Criticality
- c. Fusion.

INTRODUCTION

Nuclear power is made possible by the process of nuclear fission. Fission is but one of a large number of nuclear reactions that can take place. Many reactions other than fission are quite important because they affect the way we deal with all aspects of handling and storing nuclear materials. These reactions include radioactive decay, scattering, and radioactive capture. This lesson is designed to provide an understanding of the forces present within an atom.

References:

1. “Nuclear Chemistry”; Harvey, B. G.

2. “Physics of the Atom”; Wehr, M: R and Richards, J. A. Jr.

3. “Introduction to Atomic and Nuclear Physics”; Oldenburg, O. and Holladay, W. G.

4. “Health Physics Fundamentals”; General Physics Corp.

5. “Basic Radiation Protection Technology”; Gollnick, Daniel; Pacific Radiation Press; 1994.

6. “Fundamental Manual Vol. 1”; Defense Reactor Training Program, Entry Level Training Program.

7. “Introduction to Health Physics”; Cember, Herman; 2nd ed.; Pergamon Press; 1983.

8. ANL-88-26 (1988) “Operational Health Physics Training”; Moe, Harold; Argonne National Laboratory, Chicago.

9. NAVPERS 10786 (1958) “Basic Nuclear Physics”; Bureau of Naval Personnel.

1.04.01 Define the following terms:

- ***a. Nucleon***
- ***b. Nuclide***
- ***c. Isotope.***

NUCLEAR TERMINOLOGY

There are several terms used in the field of nuclear physics that an RCT must understand.

Nucleon

Neutrons and protons are found in the nucleus of an atom and for this reason, are collectively referred to as *nucleons.* A nucleon is defined as a constituent particle of the atomic nucleus, either a neutron or a proton.

Nuclide

A species of an atom characterized by the constitution of its nucleus, which is specified by its atomic mass and atomic number (Z), or by its number of protons (Z), number of neutrons (N), and energy content. A listing of all nuclides can be found on the “Chart of the Nuclides,” which will be introduced in a later lesson.

Isotope

This term was mentioned in Lesson 1.03 when we discussed the concepts of atomic mass and atomic weight. *Isotopes* are defined as nuclides which have the **same number of protons but different numbers of neutrons**. Therefore, any nuclides that have the same atomic number (i.e., the same element) but different atomic mass numbers are isotopes.

For example, hydrogen has three isotopes, known as *protium*, *deuterium* and *tritium*. Because hydrogen has one proton, any hydrogen atom will have an atomic number of 1. However, the atomic mass numbers of the three isotopes are different: protium (^{1}H) has mass number of 1 (1 proton, no neutrons), deuterium (D or ^{2}H) has a mass number of 2 (1 proton, 1 neutron), and tritium (T or ^{3}H) has a mass number of 3 (1 proton, 2 neutrons).

1.04.02 Identify the basic principles of the mass-energy equivalence concept.

MASS-ENERGY EQUIVALENCE

Of fundamental concern in nuclear reactions, such as ^{235}U fission, is the question of whether a given reaction is possible and, if so, how much energy is required to initiate the reaction or is released when the reaction occurs. The key to these questions lies in the relationship between the mass and energy of an object.

The theory that relates the two was proposed by Albert Einstein in 1905. Einstein's special theory of relativity culminated in the famous equation:

$$E = mc^2$$

where:

E = Energy

m = mass

c = speed of light

This equation expresses the equivalence of mass and energy, meaning that **mass may be transformed to energy and vice versa**. Because of this equivalence the two are often referred to collectively as *mass-energy*.

The *mass-energy equivalence* theory implies that **mass and energy are interchangeable**. The theory further states that **the mass of an object depends on its speed**. Thus, all matter contains energy by virtue of its mass. It is this energy source that is tapped to obtain nuclear energy.

The Law of Conservation of Energy applies to mass as well as energy, because the two are equivalent. Therefore, in any nuclear reaction, the total mass-energy is conserved, i.e., mass-energy cannot be created or destroyed. This is of importance when it becomes necessary to calculate the energies of the various types of radiation that accompany the radioactive decay of nuclei.

Pair Annihilation: An Example of Mass to Energy Conversion

An interaction which occurs is pair *annihilation,* where two particles with mass, specifically a *positron* and an electron (negatron), collide and are transformed into two rays (photons) of electromagnetic energy. A positron is an anti-electron, having a positive electrical charge. When a positron collides with an electron, both particles are annihilated, and their mass is converted completely into electromagnetic energy. (This interaction will be discussed in Lesson 1.07, "Interactions of Radiation with Matter.")

If the mass of an electron/positron is 0.00054858026 amu the resulting annihilation energy (radiation) resulting from the collision would be:

$$\frac{2(0.00054858026\ amu)}{1} \times \frac{931.478 MeV}{amu} = 1.022\ MeV$$

(1 amu is equal to 1/12 of the mass of an atom of the isotope carbon-12.

Thus, 1 amu = 1.660 33x10^{-27} kg. Also, 1 amu = 931.478 MeV)

1.04.03 Define the following terms:

- ***a. Mass defect***
- ***b. Binding energy***
- ***c. Binding energy per nucleon.***

MASS DEFECT AND BINDING ENERGY

With an understanding of the equivalence of mass and energy, we can now examine the principles which lie at the foundation of nuclear power.

Mass Defect

As we said earlier, the mass of an atom comes almost entirely from the nucleus. If a nucleus could be disassembled to its constituent parts, i.e., protons and neutrons, it would be found that the **total mass of the atom is less than the sum of the masses of the individual protons and neutrons**. This is illustrated in Figure 1 below.

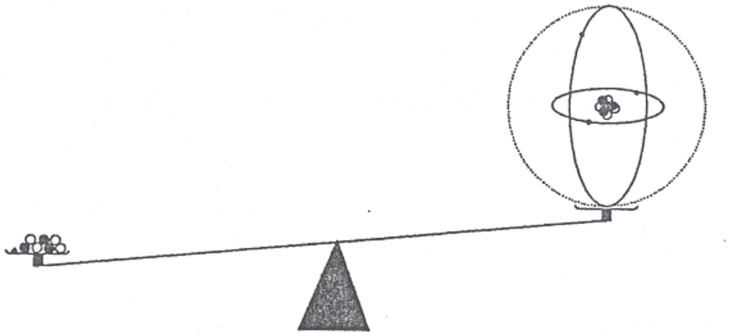

Figure 1. Atomic Scale

This slight difference in mass is known as the *mass defect*, δ (pronounced “delta”), and can be computed for each nuclide, using the following equation.

$$\delta = (Z)(M_p) + (Z)(M_e) + (A\text{-}Z)(M_n) - M_a$$

where:

δ = mass defect

Z = atomic number

M_p = mass of a proton (1.00728 amu)

M_e = mass of a electron (0.000548 amu)

A = mass number

M_n = mass of a neutron (1.00867 amu)

M_a = atomic mass (from Chart of the Nuclides)

For example, consider an isotope of lithium, ${}^{7}_{3}\text{Li}$:

A = 7

Z = 3

M = 7.01600 amu (per Chart of the Nuclides)

Therefore:

$\delta = (3)(1.00728) + (3)(0.000548) + (7\text{-}3)(1.00867) - (7.01600)$

$\delta = (3.02184) + (0.001644) + (4.03468) - (7.01600)$

$\delta = (7.058164) - (7.01600)$

$\delta = 0.042164$ amu

Binding Energy

The mass defect of ${}^{7}_{3}\text{Li}$ is 0.042164 amu. This is the mass that is apparently "missing," but, in fact, has been converted to energy; the energy that binds the lithium atom nucleus together or its *binding energy*. Binding energy is **the energy equivalent of mass defect.** From the Lesson 1.02 Conversion Tables:

$$1\ amu = 931.478\ MeV$$

So, if we multiply the mass defect by this number, we can calculate the binding energy.

$$BE = \left(\frac{0.042164\,amu}{1}\right)\left(\frac{931.478\,MeV}{amu}\right) = 39.27\,MeV$$

From this, we have determined the energy converted from mass in the formation of the nucleus. We will see that it is also the energy that must be applied to the nucleus in order to break it apart.

Another important calculation is that of the binding energy of a neutron. This calculation is of significance when the energy of the fission process is considered. For example, when U-235 absorbs a neutron, the compound nucleus U-236 is formed (see NUCLEAR FISSION later in this lesson). The change in mass (Δm) is calculated and then converted to its energy equivalent:

$\Delta m - (m_n + m_{235U}) - m_{236U}$
$\Delta m = (1.00867 + 235.0439) - 236.0456$
$\Delta m = 0.0070$ amu

0.0070 amu $\times$ 931.5 MeV/amu = 6.52 MeV

Thus, the nucleus possesses an *excitation energy* of 6.52 MeV when ^{235}U absorbs a neutron.

Binding Energy per Nucleon

If the total binding energy of a nucleus is divided by the total number of nucleons in the nucleus, the *binding energy per nucleon* is obtained. This represents the average energy that must be supplied in order to remove a nucleon from the nucleus. For example, using the ${}^{7}_{3}\mathrm{Li}$ atom as before, the binding energy per nucleon would be calculated as follows:

$$\frac{39.27\ MeV}{7\ nucleons} = 5.61\,MeV\ per\ nucleon$$

If the binding energy per nucleon is plotted as a function of mass number (total number of nucleons) for each element, a curve is obtained (see Figure 2). The binding energy per nucleon peaks at about 8.5 MeV for mass numbers 40–120 and decreases to about 7.6 MeV per nucleon for uranium.

The binding energy per nucleon decreases with increasing mass number above mass 56 because as more protons are added, the proton-proton repulsion increases faster than the nuclear attraction. Because the repulsive forces are increasing, less energy must be supplied on the average to remove a nucleon. That is why there are no *stable* nuclides with mass numbers beyond that of 208.

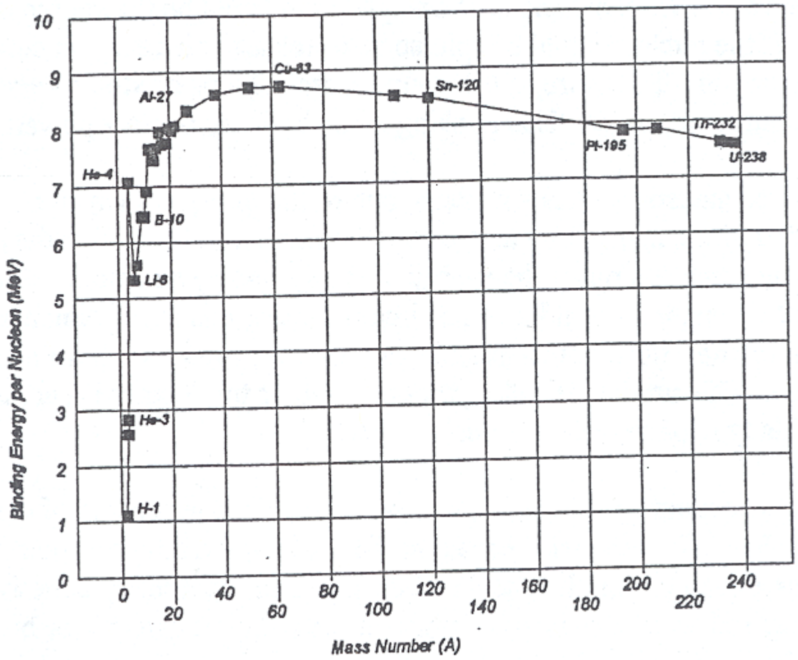

Figure 2. Binding Energy vs. Mass Number

NUCLEAR TRANSFORMATION EQUATIONS

Using the $^{A}_{Z}X$ format, equations can be written that depict a transformation that has occurred in a nucleus or nuclei. Because it is an equation, both sides must be equal. Therefore, the total mass-energy on the left must be equal to the total mass-energy on the right. Keeping in mind that mass and energy are equivalent, any difference in total mass is accounted for as energy released in the transformation. This energy release is called the *Q* value. For example, the *alpha decay* of radium-226 would be depicted as:

$$^{226}_{88}Ra \rightarrow \rightarrow \rightarrow ^{222}_{86}Rn + ^{4}_{2}\alpha + Q$$

The energy release, represented by *Q* in this case, is manifest as the kinetic energy of the high-speed alpha particle as well as the recoil of the radon-222 atom.

1.04.04 Define the following terms

a. Fission
b. Criticality
c. Fusion.

NUCLEAR FISSION

As we have shown, the nucleus of a single atom could be the source of considerable energy. If the nucleus could be split so as to release this energy it could be used to generate power. Therefore, if the energy from millions of atoms were released, it would be a great source of power. This thinking is the basis for nuclear power.

When a free neutron strikes a nucleus, one of the processes that may occur is the *absorption* of the neutron by the nucleus. It has been shown that the absorption of a neutron by a nucleus raises the energy of the system by an amount equal to the binding energy of the neutron. Under some circumstances, this absorption may result in **the splitting of the nucleus into at least two smaller nuclei with an accompanying release of energy**. This process is called *fission*. Two or three neutrons are usually released during this type of transformation.

In order to account for how this process is possible, use is made of the observation that the nucleus, in many ways, resembles a drop of liquid. The drop of liquid is held together by cohesive forces between molecules, and when the drop is deformed the cohesive forces may be insufficient to restore the drop to its original shape. However, when sufficiently deformed, the splitting of the drop may occur. Figure 3 – *d*. and *e*., illustrate this model.

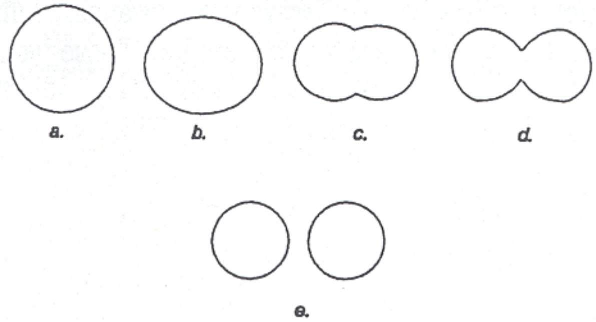

Figure 3. Liquid Drop Model of Fission

The absorption of a neutron raises the energy of the system by an amount equal to the binding energy of the neutron. This energy input causes deformation of the nucleus, but if it is not of sufficient magnitude, the nucleon-nucleon attractive forces will act to return the nucleus to its original shape. If the energy input is sufficiently large, the nucleus may reach a point of separation, and fission would ensue. The energy required to drive the nucleus to the point of separation is called the *critical energy for fission,* E_c, The values of E_c, for various nuclei can be calculated, based on the knowledge of the forces that act to hold the nucleus together.

An example of fission is shown below, involving neutron absorption by ^{235}U:

$$ {}^{235}_{92}U + {}^{1}_{0}n \rightarrow \rightarrow \rightarrow {}^{236}_{92}U^{*} \rightarrow \rightarrow \rightarrow {}^{138}_{56}Ba + {}^{95}_{36}Kr + 3\left({}^{1}_{0}n\right) + Q $$

On the average, approximately 200 MeV of energy is released per fission.

The fission process can be “energetically” explained by comparing the critical energy for fission with the amount of energy input, i.e., the neutron binding energy. For ^{238}U and ^{232}Th, the critical energy for fission is greater than the neutron binding energy: Therefore, an additional amount of energy must be supplied in order for fission to occur in these nuclei. This additional energy is in the form of neutron kinetic energy and confirms the observation that fission occurs in these fissionable nuclei only when the neutron has approximately 1 MeV of kinetic energy.

The situation is quite different for ^{235}U, ^{233}U, and ^{239}Pu. In these cases, the neutron binding energy exceeds the critical energy for fission. Thus, these nuclei may be fissioned by *thermal* or very low energy (0.025 eV) neutrons.

As mentioned earlier, the new elements that are formed as a result of the fission of an atom are unstable because their neutron/proton ratios are too high. To attain stability, the fission fragments will undergo various transformations depending on the degree of instability. Along with the neutrons immediately released during fission, a highly unstable element may give off several neutrons to try to regain stability. This, of course, makes more neutrons available to cause more nuclei to fission and is the basis for the *chain reaction* used to produce nuclear power. The excited fission product nuclei will also give off other forms of radiation in order to achieve stable energy levels. These include beta and gamma radiation.

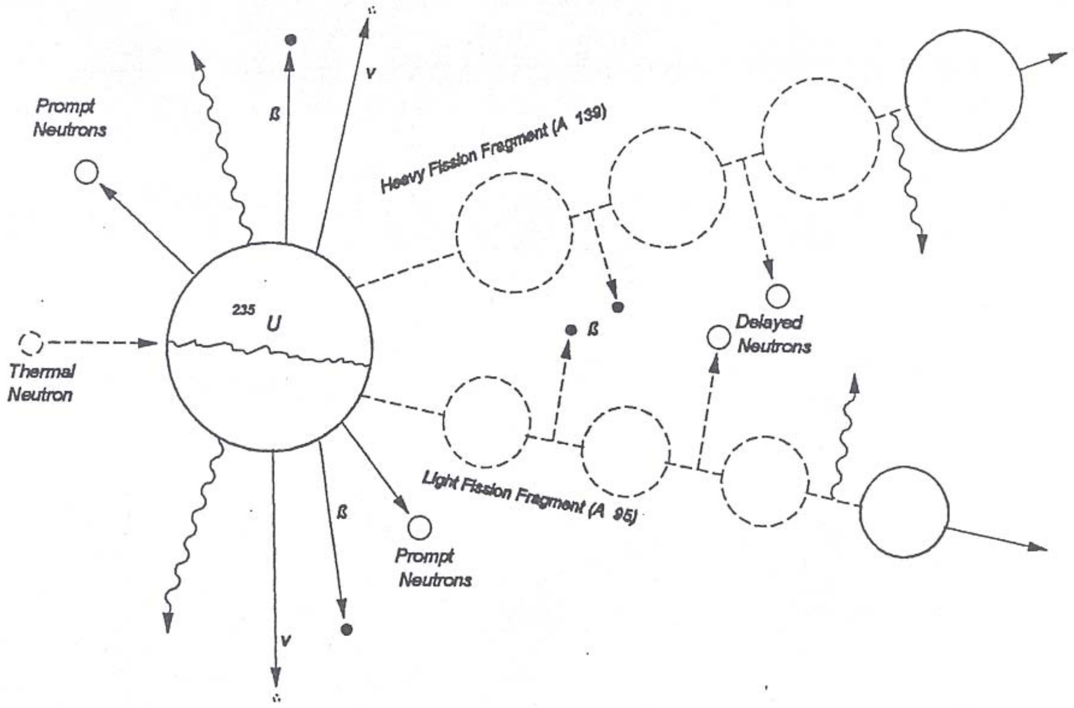

Figure 4. Fission process in ^{235}U initiated by a thermal neutron.

Criticality

Criticality is the condition in which the neutrons produced by fission are equal to the number of neutrons in the previous generation. This means that the neutrons in one generation go on to produce an equal number of fission events, which events in turn produce neutrons that produce another generation of fissions, and so forth. This continuation results in the self-sustained chain reaction mentioned above. Figure 5 gives a simple illustration of the chain reaction that occurs in a criticality.

As one can discern, this reaction requires control. If the population of neutrons remains constant, the chain reaction will be sustained. The system is thus said to be *critical*. However, if too many neutrons escape from the system or are absorbed but do not produce a fission, then the system is said to be *sub-critical*, and the chain reaction will eventually stop.

On the other hand, if the two or three neutrons produced in one fission each go on to produce another subsequent fission, the number of fissions and the production of neutrons will increase exponentially. In this case the chain reaction is said to be *supercritical*.

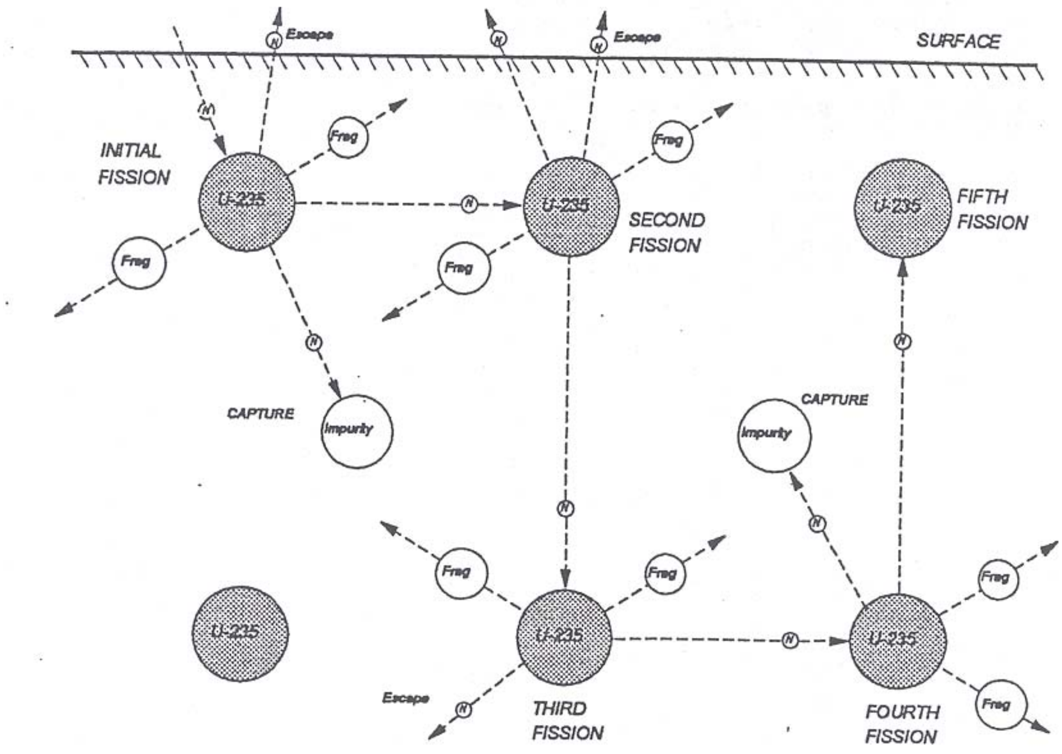

Figure 5. Self-sustaining Chain Reaction

In nuclear reactors, this concept is expressed as the *effective multiplication constant* or K_{eff}. K_{eff} is defined as the ratio of the number of neutrons in the reactor in one generation to the number of neutrons in the previous generation. On the average, 2.5 neutrons are emitted per uranium fission. If K_{eff} has a value of greater than 1, the neutron flux is increasing, and conversely, if it has a value of less than 1, the flux is decreasing with time. Table 1 illustrates the reactor condition for various values of the multiplication constant.

Table 1. The Effective Multiplication Constant

K_{eff} = Effective Multiplication Constant
$K_{eff} <1$ = Subcritical Condition
$K_{eff} = 1$ = Critical Condition
$K_{eff} >1$ = Supercritical Condition

In a sub-critical reactor, the neutron flux and power output will die off in time. When critical, the reactor operates at a steady neutron and power output. A reactor must be supercritical to increase the neutron flux and power level.

Therefore, the population of neutrons must be controlled in order to control the number of fissions that occur. Otherwise, the results could be devastating.

Fusion

Another reaction between nuclei that can be the source of power is *fusion.* Fusion is the act of combining or "fusing" two or more atomic nuclei. Fusion thus builds atoms. The process of fusing nuclei into a larger nucleus with an accompanying release of energy is called fusion.

Fusion occurs naturally in the sun and is the source of its energy. The reaction is initiated under the extremely high temperatures and pressure in the sun whereby hydrogen nuclei fuse together generating helium nuclei. The process of hydrogen fusion into helium results in an enormous amount of energy liberated in the form of the kinetic energy of the reaction products, i.e. the heat.

$$4\left({}_{1}^{1}H\right) \rightarrow \rightarrow \rightarrow {}_{2}^{4}He^{2+} + 2(e^{+}) + 24.7\ MeV$$

What occurs in the above equation is the combination of 4 hydrogen nuclei, giving a total of 4 protons and 4 electrons. Then 2 protons combine with 2 electrons to form 2 neutrons, which combined with the remaining 2 protons form a helium nucleus, leaving 2 electrons and a release of energy.