A. PRINCIPLE OF REACTOR OPERATION

ENABLING OBJECTIVES:

2.1	Explain how heat is produced by nuclear fission.
2.2	Describe what is meant by sub-critical, critical, and super-critical operation.
2.3	Explain the purpose of a moderator.
2.4	Explain the significance of the reactor core geometry.

ATOMIC STRUCTURE

All matter is composed of tiny particles called atoms. These atoms are in turn composed of more fundamental particles, the **proton**, the **neutron**, and the **electron**. A proton is a very small particle and carries a single positive charge (+1e) and a mass of one mass unit (1u)[1]. A neutron is an uncharged (neutral) particle of the same size and approximately the same mass as the proton.[2] An electron is the smallest of the three fundamental particles, having a mass of about 1/1840 of the mass of a nucleon[3] and carries a single negative charge (-1e).[4] Figure 2.1 shows the basic atomic structure of hydrogen, helium and lithium elements. The nucleus contains a proton or a combination of neutrons and protons, surrounded by negatively charged orbiting electrons. Most naturally occurring elements found around us are made of stable atoms. A few naturally occurring elements are unstable, though most unstable elements are manmade.

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[1] The mass of a proton is 1.0073u. Most of the time this is rounded off to 1u which equals 1.66×10^{-27} kg.

[2] A neutron has a mass of 1.0087u.

[3] A nucleon is a name used for either of the two heavier particles (proton, neutron).

[4] The electronic charge is given by $1e = 1.602 \times 10^{-19}$ Coulombs.

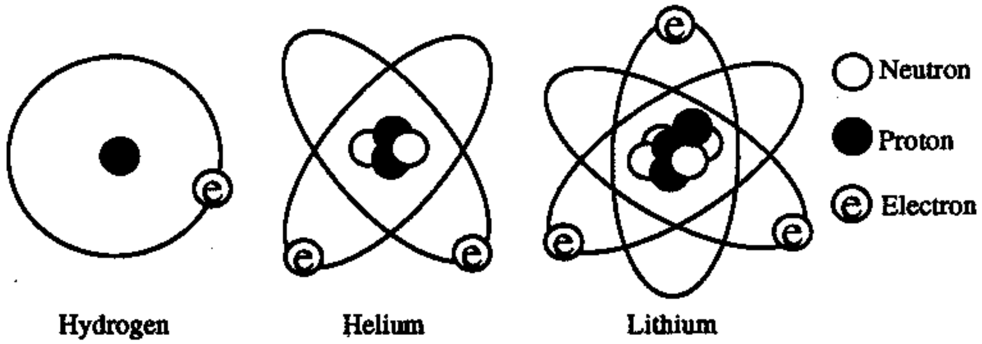
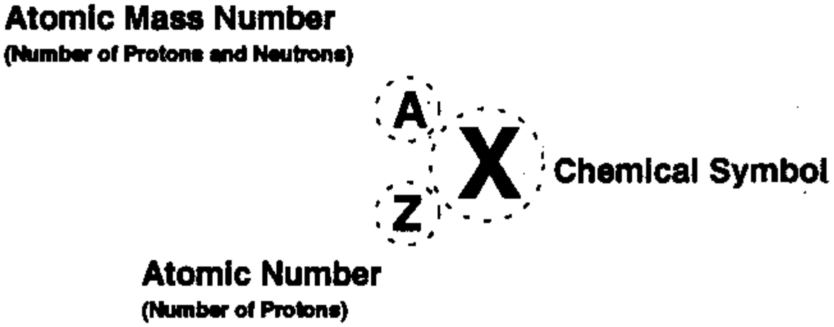


Figure 2.1
Atomic Structure

An element is identified by its individual chemical symbol, its atomic number (number of protons), and its atomic mass number (total number of protons and neutrons) as follows:



The three elements in Figure 2.1 are represented as:

Hydrogen $^{1}_{1}H$ (1 proton),

Helium $^{4}_{2}He$ (2 protons, 2 neutrons),

Lithium $^{7}_{3}Li$ (3 protons, 4 neutrons).

The number of protons in an element determines the chemical symbols. $^{4}_{2}He$ can be rewritten as He-4 or helium-4.

When an atom is represented by showing the atomic and mass numbers, it is called a **nuclide**. An atom of an element with a different number of neutrons is called an **isotope** of that particular element. All isotopes of a given element have similar chemical and physical properties but show very large variations in nuclear properties.

The two major elements that are of particular significance in this course are hydrogen and uranium. Deuterium ($^{2}_{1}H$ or D), an isotope of hydrogen, in the form of heavy water (D_2O), is needed to make the CANDU reactor work. Another isotope of hydrogen formed during operation is tritium. Tritium ($^{3}_{1}H$), which is radioactive, is produced when a deuterium atom in the heavy water captures a neutron that is released during reactor nuclear processes. Uranium is used for CANDU fuel. It has two naturally occurring isotopes, $^{238}_{92}U$ and $^{235}_{92}U$. Of the two isotopes, U-235 will fission.

FISSION

In 1939 scientists discovered that when U-235 was bombarded with neutrons some of the nuclei would split into two smaller nuclei of medium mass with two important results:

- Energy was released,
- Additional neutrons were released.

The process was called **fission** which is defined as the splitting of a heavy nucleus into two lighter nuclei.

A typical fission is shown in figure 2.2. A neutron enters the U-235 nucleus to form a highly excited nucleus that fissions into two smaller nuclei forming new elements known as **fission products**. In addition more neutrons are released as well as electromagnetic radiation in the form of gamma rays (γ). There are many possible fission reactions and therefore a wide variety of fission products are produced. The majority are unstable and decay with time to other products (known as fission product daughters) with a release of radiation. Many of these fission products will absorb neutrons.

Where does the energy come from in this fission reaction? It is a result of Einstein's famous equation ($E= mc^2$) which equates mass and energy. A comparison of the mass of the reactants (U-235 + neutron) to the mass of the products (fission products + neutrons) will show a discrepancy. The products have less mass and that lost mass appears as energy which we recover as heat.

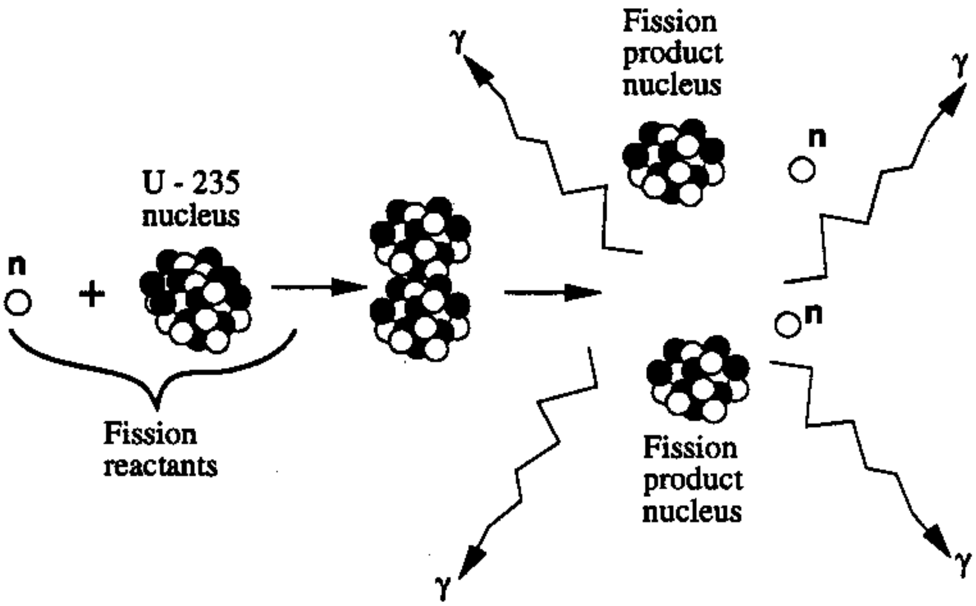


Figure 2.2
Fission

A typical fission produces about 200 MeV (Mega electron volt) of energy if the energy from the subsequent radioactive decay is included. This is not a significant amount of energy but each kilogram of natural uranium contains an enormous number (1.8×10^{22}) of U-235 atoms, most of which can be fissioned. The number of fissions per second determines the power produced. For example, each watt of power requires 3.1×10^{10} fissions per second.

CHAIN REACTION

Each fission will produce between 0 and 5 neutrons; or an average of approximately 2.5. It is these neutrons that can, under the right circumstances, go on to produce further fissions. As figure 2.3 shows, using the assumption of 2 neutrons released per fission, one fission gives two, two gives four, four gives eight and so on. This would give over one thousand fissions in just ten generations.

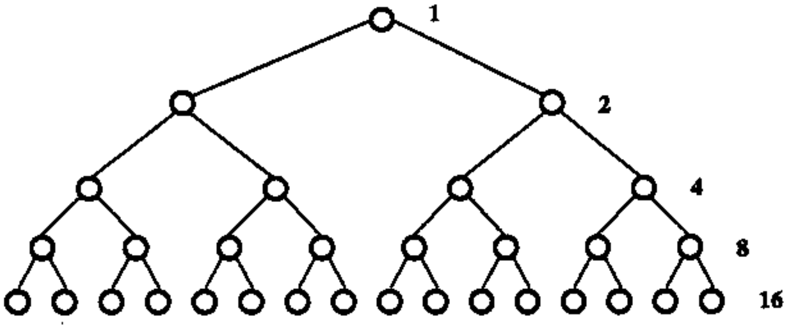


Figure 2.3
The Chain Reaction

This type of neutron multiplication (chain reaction) is not suitable for steady state power production. For steady reactor power, we want each fission to cause just one other fission; the remaining neutrons must meet some fate other than causing fission. Many neutrons meet this fate quite naturally. Some neutrons are lost through **parasitic absorption** where the neutrons are absorbed by materials or fission products in the reactor. One fission product of particular interest is the high neutron absorbing Xenon-135. Some material in the reactor becomes radioactive upon absorbing neutrons, producing **activated products** (especially activated corrosion products). Other neutrons escape the reactor core into the shielding as **leakage**.

CRITICALITY AND NEUTRON MULTIPLICATION

In the chain reaction illustrated in figure 2.4, only one neutron is available each time to cause fission. Therefore, the number of fissions occurring per second remains constant.

A nuclear reactor can operate with **steady, increasing** or **decreasing** reactor power. Let us look at each of these states!

a) When the chain reaction is producing neutrons such that only one neutron is available for further fission reactions in each generation, the power will be steady and the reactor is said to be **critical**. Notice from this definition that the reactor may be critical (i.e operating at steady state) at any power level.

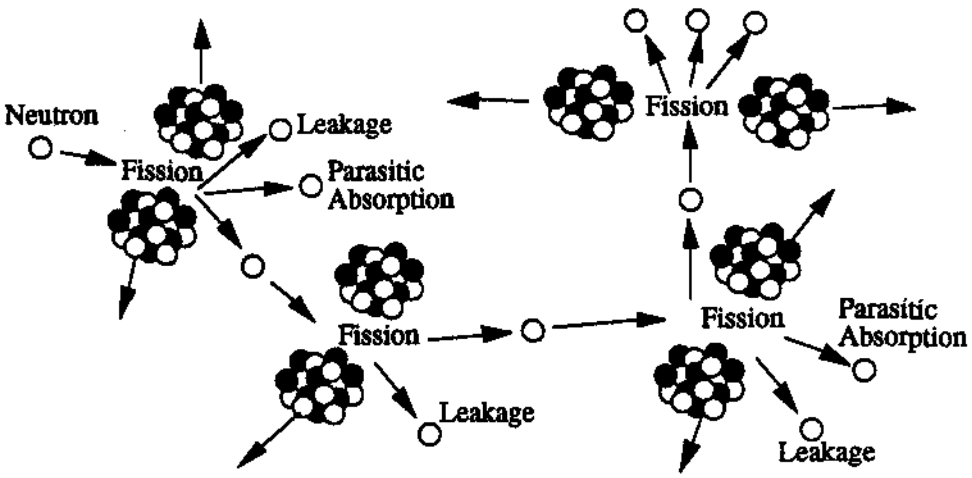


Figure 2.4
A Chain Reaction

b) Let us now consider a chain reaction where, for every 100 fissions, 105 neutrons become available for second generation fissions. If this rate of multiplication continues in the succeeding generations, there will be a greater number of induced fissions and consequently a larger neutron population from one generation to the next. After 100 generations, for example, the numbers of neutrons present would be 13150.

The arithmetic is just like compound interest buildup in a daily interest bank account. A few neutrons could thus initiate a growing chain of fissions. The power increases and the reactor is said to be **super-critical**. In the above example power increased 131 times in about one tenth of a second. This is too fast a rate to control and in practice the rate of increase is kept much lower.

c) Finally, let us consider the case where the number of neutrons is reduced in the second generation from 100 to 95. In this situation, the original 100 neutrons would be reduced to one in about 90 generations. The number of fissions decreases as the neutron population reduces. The chain reaction cannot be maintained and the power decreases. The reactor is then said to be **sub-critical**.

Note that the rate of neutron multiplication is not constant if the power is being increased or decreased. It is only constant when the power is steady at some set value.

We have just described the different power states of the reactor (i.e., critical, super-critical and sub-critical) using the rate of neutron production from one generation to the next. In practice, we define these power states in terms of reactivity or Δk, a factor directly related to neutron multiplication as expressed in the following equation:

$$\Delta k = \frac{\text{Change in number of neutrons from one generation to the next generation}}{\text{Number of neutrons in the preceding generation}}$$

Δk takes on small negative or positive values depending on whether the neutron population is decreasing or increasing from generation to generation. We can say that the reactor is:

Critical if	$\Delta k = 0$
Super-critical if	$\Delta k > 0$ (positive reactivity)
Sub-critical if	$\Delta k < 0$ (negative reactivity)

Reactivity is normally given in units of milli-k (mk), where 1 mk = 10^{-3} or $\frac{1}{1000}k$.

Example

If k = 1.005, then $\Delta k = 0.005$ or 5 mk

THE REACTOR CORE

FUEL

When each fission produces at least one neutron that causes a subsequent fission, we have a self-sustaining chain reaction. In order for this to occur we need a critical mass. For example, take a small pile of U-235 and initiate fission. Many neutrons would escape from the pile before causing further fissions and the chain reaction would die away. As more U-235 is added to our pile, fewer neutrons will escape and at some point the pile will be large enough to support a self-sustaining chain reaction. A pile of that size is the critical mass of U-235.

None of the reactors used world wide to produce power use pure U-235 as fuel. In our case, CANDUs use natural uranium that contains 0.7% U-235 with the balance (i.e., 99.3%) as U-238 (U-238 does not undergo fission like U-235). Natural uranium with its tiny amount of fissile U-235 cannot be made critical on its own because too many of the neutrons produced in fission of the U-235 are absorbed by the U-238.

It is more difficult to support a chain reaction in a CANDU reactor because we use natural uranium fuel. Why did Canadian designers decide to use natural uranium in the fuel? First, natural uranium is an inexpensive fuel. Second, after World War II, Canada was one of the few countries that knew how to build a nuclear bomb. By choosing a design that did not require uranium enrichment, Canadian politicians showed clearly that we were not going to begin making bombs.

MODERATOR

To enable fission using natural uranium fuel, we make use of a **moderator**. The moderator surrounds the fuel and enables the fast neutrons resulting from fission to escape the fuel and travel in the moderator momentarily before entering the fuel again. During their time in the moderator the neutrons are **thermalized** (slowed to a low energy level) so that on return to the fuel, they will not be absorbed by the U-238. Slow neutrons are also more likely to be absorbed in U-235 causing fission than are fast neutrons.

Neutrons lose their energy in collision with other nuclei and to be effective a moderator must thermalize neutrons in as few collisions as possible over a short distance. Elastic scattering of neutrons with light nuclei is a more efficient method of moderation than elastic scattering with heavy nuclei. What do we mean by elastic scattering? Elastic scattering means that in the collision between the neutron and another nucleus the neutron transfers some of its energy to the struck nuclei but between the two particles energy is conserved. If the struck nucleus is light[5], it will receive a larger portion of the neutron's energy. For example, in pure hydrogen it takes 18 collisions to thermalize (i.e., slow) a fission neutron, but in U-238 it takes 2172 collisions.

Water is a relatively light material and abundantly available. Can it be used as a moderator? Normal or light water will thermalize fission neutrons in about 20 collisions but unfortunately it also absorbs some neutrons. For natural uranium, light water absorbs too many neutrons to allow a critical mass to be established. If light water is chosen as a moderator, then the amount of U-235 in the fuel must be increased to 2-3%.

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[5] Has a mass comparable to the neutron.

We have already noted that CANDU uses natural uranium. What do we do about a moderator? We use a form of water called heavy water (D_2O) which is made from deuterium. D_2O can thermalize neutrons in 36 collisions and pure D_2O is nearly 700 times less likely to absorb neutrons than is ordinary water. Natural uranium with a heavy water moderator enables a self-sustaining chain reaction.

CORE GEOMETRY

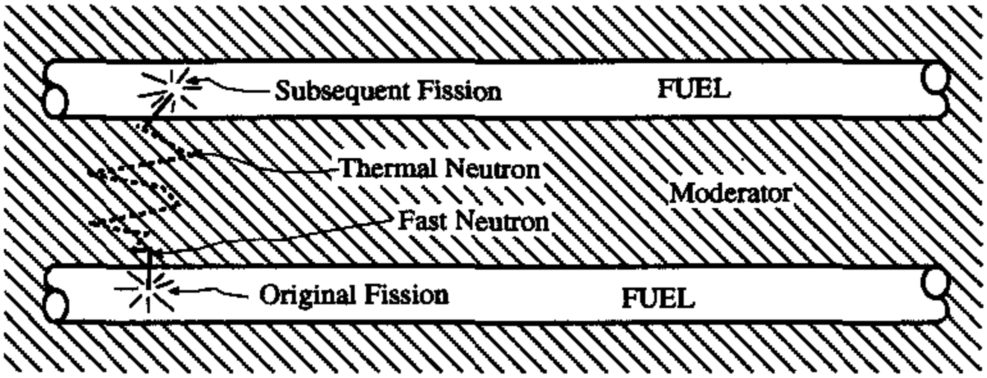

Figure 2.5
Axial Reactor Arrangement

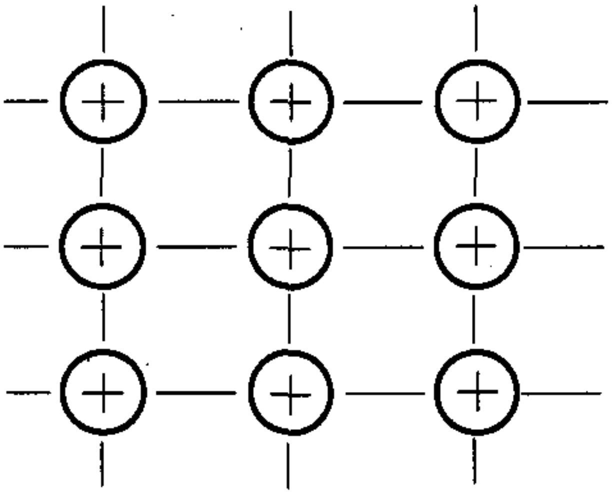

Figure 2.6
Radial Fuel Arrangement

Figures 2.5 and 2.6 show the axial and radial arrangement of the fuel in the moderator. This arrangement permits the fast neutrons from fission to leave the fuel and enter the moderator before significant absorption by U-238 occurs. The neutrons are then thermalized in the moderator before reentering the fuel. This arrangement accomplishes two goals:

1. It slows down neutrons to thermal energy levels where the fission of U-235 is significantly higher, and
2. it minimizes neutron absorption by:
   - keeping the neutrons away from the U-238 while they are at an energy where they are easily absorbed,
   - returning the neutrons quickly to the fuel to reduce absorption in the moderator.

The channel spacing shown in figure 2.6 is very important and is carefully chosen for CANDU reactors such that any significant increase or decrease in this spacing will decrease the probability of sustaining a chain reaction. An important safety feature is that our fuel can only be made critical in heavy water in an arrangement similar to the one used. There is no chance of attaining a critical mass in the handling or storage of CANDU fuel.

ASSIGNMENT

1. Where does the heat come from in fission?

2. What is critical operation?

3. How does a moderator enable us to achieve a self-sustaining chain reaction using natural uranium?

4. If the arrangement of fuel in the reactor core was significantly altered, what effect would this have on the chain reaction?