NEUTRON MODERATION

In thermal reactors, the neutrons that cause fission are at a much lower energy than the energy level at which they were born from fission. In this type of reactor, specific materials must be included in the reactor design to reduce the energy level of the neutrons in an efficient manner.

EO 2.12 DEFINE the following concepts:

a. Thermalization
b. Moderator
c. Moderating ratio
d. Average logarithmic energy decrement
e. Macroscopic slowing down power

EO 2.13 LIST three desirable characteristics of a moderator.

EO 2.14 Given an average fractional energy loss per collision, CALCULATE the energy loss after a specified number of collisions.

Neutron Slowing Down and Thermalization

Fission neutrons are produced at an average energy level of 2 MeV and immediately begin to slow down as the result of numerous scattering reactions with a variety of target nuclei. After a number of collisions with nuclei, the speed of a neutron is reduced to such an extent that it has approximately the same average kinetic energy as the atoms (or molecules) of the medium in which the neutron is undergoing elastic scattering. This energy, which is only a small fraction of an electron volt at ordinary temperatures (0.025 eV at 20°C), is frequently referred to as the thermal energy, since it depends upon the temperature. Neutrons whose energies have been reduced to values in this region (< 1 eV) are designated thermal neutrons. The process of reducing the energy of a neutron to the thermal region by elastic scattering is referred to as *thermalization*, slowing down, or moderation. The material used for the purpose of thermalizing neutrons is called a *moderator*. A good moderator reduces the speed of neutrons in a small number of collisions, but does not absorb them to any great extent. Slowing the neutrons in as few collisions as possible is desirable in order to reduce the amount of neutron leakage from the core and also to reduce the number of resonance absorptions in non-fuel materials. Neutron leakage and resonance absorption will be discussed in the next module.

The ideal moderating material (moderator) should have the following nuclear properties.

- large scattering cross section
- small absorption cross section
- large energy loss per collision

A convenient measure of energy loss per collision is the logarithmic energy decrement. The *average logarithmic energy decrement* is the average decrease per collision in the logarithm of the neutron energy. This quantity is represented by the symbol ξ (Greek letter xi).

$$\xi = \ln E_i - \ln E_f$$

$$\xi = \ln \left(\frac{E_i}{E_f} \right) \qquad (2\text{-}8)$$

where:

ξ = average logarithmic energy decrement
E_i = average initial neutron energy
E_f = average final neutron energy

The symbol ξ is commonly called the average logarithmic energy decrement because of the fact that a neutron loses, on the average, a fixed fraction of its energy per scattering collision. Since the fraction of energy retained by a neutron in a single elastic collision is a constant for a given material, ξ is also a constant. Because it is a constant for each type of material and does not depend upon the initial neutron energy, ξ is a convenient quantity for assessing the moderating ability of a material.

The values for the lighter nuclei are tabulated in a variety of sources. The following commonly used approximation may be used when a tabulated value is not available.

$$\xi = \frac{2}{A + \frac{2}{3}}$$

This approximation is relatively accurate for mass numbers (A) greater than 10, but for some low values of A it may be in error by over three percent.

Since ξ represents the average logarithmic energy loss per collision, the total number of collisions necessary for a neutron to lose a given amount of energy may be determined by dividing ξ into the difference of the natural logarithms of the energy range in question. The number of collisions (N) to travel from any energy, E_{high}, to any lower energy, E_{low}, can be calculated as shown below.

$$N = \frac{\ln E_{high} - \ln E_{low}}{\xi}$$

$$= \frac{\ln \left(\frac{E_{high}}{E_{low}} \right)}{\xi}$$

Example:

How many collisions are required to slow a neutron from an energy of 2 MeV to a thermal energy of 0.025 eV, using water as the moderator? Water has a value of 0.948 for ξ.

Solution:

$$N = \frac{\ln \left(\frac{E_{high}}{E_{low}} \right)}{\xi}$$

$$= \frac{\ln \left(\frac{2 \times 10^6 \text{ eV}}{0.025 \text{ eV}} \right)}{0.948}$$

$$= 19.2 \text{ collisions}$$

Sometimes it is convenient, based upon information known, to work with an average fractional energy loss per collision as opposed to an average logarithmic fraction. If the initial neutron energy level and the average fractional energy loss per collision are known, the final energy level for a given number of collisions may be computed using the following formula.

$$E_N = E_o (1 - x)^N \tag{2-9}$$

where:

E_o = initial neutron energy
E_N = neutron energy after N collisions
x = average fractional energy loss per collision
N = number of collisions

Example:

If the average fractional energy loss per collision in hydrogen is 0.63, what will be the energy of a 2 MeV neutron after (a) 5 collisions? (b) 10 collisions?

Solution:

a)

$$E_N = E_o (1 - x)^N$$

$$E_5 = (2 \text{ x } 10^6 \text{ eV}) (1 - 0.63)^5$$

$$= 13.9 \text{ keV}$$

b)

$$E_N = E_o (1 - x)^N$$

$$E_{10} = (2 \text{ x } 10^6 \text{ eV}) (1 - 0.63)^{10}$$

$$= 96.2 \text{ eV}$$

Macroscopic Slowing Down Power

Although the logarithmic energy decrement is a convenient measure of the ability of a material to slow neutrons, it does not measure all necessary properties of a moderator. A better measure of the capabilities of a material is the macroscopic slowing down power. The *macroscopic slowing down power* (MSDP) is the product of the logarithmic energy decrement and the macroscopic cross section for scattering in the material. Equation (2-10) illustrates how to calculate the macroscopic slowing down power.

$$MSDP = \xi \Sigma_s \tag{2-10}$$

Moderating Ratio

Macroscopic slowing down power indicates how rapidly a neutron will slow down in the material in question, but it still does not fully explain the effectiveness of the material as a moderator. An element such as boron has a high logarithmic energy decrement and a good slowing down power, but it is a poor moderator because of its high probability of absorbing neutrons.

The most complete measure of the effectiveness of a moderator is the moderating ratio. The *moderating ratio* is the ratio of the macroscopic slowing down power to the macroscopic cross section for absorption. The higher the moderating ratio, the more effectively the material performs as a moderator. Equation (2-11) shows how to calculate the moderating ratio of a material.

$$MR = \frac{\xi \, \Sigma_s}{\Sigma_a} \qquad (2\text{-}11)$$

Moderating properties of different materials are compared in Table 2.

TABLE 2
Moderating Properties of Materials

Material	ξ	Number of Collisions to Thermalize	Macroscopic Slowing Down Power	Moderating Ratio
H_2O	0.927	19	1.425	62
D_2O	0.510	35	0.177	4830
Helium	0.427	42	9×10^{-6}	51
Beryllium	0.207	86	0.154	126
Boron	0.171	105	0.092	0.00086
Carbon	0.158	114	0.083	216

Summary

The important information in this chapter is summarized below.

Neutron Moderation Summary

- Thermalization is the process of reducing the energy level of a neutron from the energy level at which it is produced to an energy level in the thermal range.
- The moderator is the reactor material that is present for the purpose of thermalizing neutrons.
- Moderating ratio is the ratio of the macroscopic slowing down power to the macroscopic cross section for absorption.
- The average logarithmic energy decrement (ξ) is the average change in the logarithm of neutron energy per collision.
- Macroscopic slowing down power is the product of the average logarithmic energy decrement and the macroscopic cross section for scattering.
- There are three desirable characteristics of a moderator.

  1. large scattering cross section
  2. small absorption cross section
  3. large energy loss per collision

- The energy loss after a specified number of collisions can be calculated using the equation below.

$$E_N = E_o \, (1 - x)^N$$