Moderator & Moderator System

K.S. Rajan

Professor, School of Chemical & Biotechnology

SASTRA University

Table of Contents

In this lecture, we shall discuss the choice of materials as moderators, their merits and demerits along with their implication in the design of a nuclear reactor. A brief description of moderator system of PHWR will also be discussed

At the end of this module, the learners will be able to

(i) understand the physics behind neutron thermalization
(ii) calculate the number of collision required for thermalization
(iii) calculate moderating ratio and compare moderators based on moderating ratio
(iv) understand the functioning of moderator system in PHWR

1 Comparison of moderators based on moderating ratio

We have seen the use of various materials as moderators in different nuclear reactors. One may also recall a reactor classification based on the moderator. That leads us to two important questions: (i) what type of materials is suitable as moderator? (ii) What is the method of comparing the performance of different materials used as moderators?

To answer the first question, we shall recollect different type of nuclear reactions.

During elastic scattering, the speed and direction of a neutron are changed due to elastic collisions with a nucleus. The neutron looses a part of its kinetic energy and hence slows down. These are the thermal neutrons that help the nuclear chain reaction to sustain. This process is called moderation.

The nucleus with which the neutrons undergo elastic collision must be conducive for thermalization. In other words, the probability of elastic reaction between neutron and the nucleus must be high. In terms of cross sections, the nuclear cross section of a moderator's nucleus for elastic scattering (σ_{el}) must be high.

Using the analogy of collisions of billiard balls for elastic scattering, it is possible to relate the mass of target or moderator nucleus (M), energy of incident neutron (E_i) and the energy of scattered neutron (E_s) using the laws of conservation of mass and energy, as follows:

$$E_s = \left(\frac{M - m_n}{M + m_n} \right)^2 E_i \tag{1}$$

If the atomic mass of the target or moderator nucleus is approximated to its mass number (A) and mass of a neutron as 1 amu, then

$$E_s = \left(\frac{A - 1}{A + 1} \right)^2 E_i \tag{2}$$

Note: The simultaneous solution of momentum and energy conservation equations for elastic collision between two bodies (as in the case of collision of a neutron with a nucleus) gives two solutions:

Solution – I: Initial and final energies of neutron are same. In this case, there is no change in the direction as neutron continues to travel in forward direction. Hence $E_s=E_i$

Solution – II: The neutron is scattered at 180° i.e. the direction of neutron is completely reversed. The energies of incident and scattered neutrons are related by equation (1)

In reality, the direction of scattering may range from 0 to 180 °. Hence, the average energy of scattered neutron may be taken as the average of energies with scattering angle 0 and 180°.

Therefore,

$$E_s = \frac{E_i + \left(\frac{A-1}{A+1}\right)^2 E_i}{2} = E_i \frac{1+\left(\frac{A-1}{A+1}\right)^2}{2} \tag{3}$$

$$\frac{E_s}{E_i} = \frac{1+\left(\frac{A-1}{A+1}\right)^2}{2} = \frac{A^2+1}{A^2+2A+1} \tag{4}$$

The above equation can be graphically represented as shown in figure 1.

From figure 1 it is clear that lower the value of 'A', lower is the E_s/E_i ratio. Hence light nuclei are more effective in moderating compared to that of heavy nuclei. This is the rationale for using water (hydrogen as scattering nucleus), heavy water (deuterium as scattering nucleus) and graphite (carbon as scattering nucleus).

Equations (1) to (4) give the ratio of kinetic energies of scattered and incident neutron after one collision. However to thermalize the neutrons by reducing its energy from few MeV to 0.0253 eV (8-orders decrease in kinetic energy) the neutron must undergo several successive elastic collisions with the moderator.

The mean logarithmic energy decrement (ξ) defined as $\ln(E_i/E_s)$ is related to the mass number of moderator as:

$$\xi = 1 - \frac{(A-1)^2}{2A}\ln\left(\frac{A+1}{A-1}\right) \tag{5}$$

Higher the value of ξ, more effective the moderation is due to the lower energy of scattered neutron compared to the incident neutron. Equation (5) can be represented diagrammatically in Figure 2. It is clear from figure 2 that ξ is high for nuclei of lower atomic number.

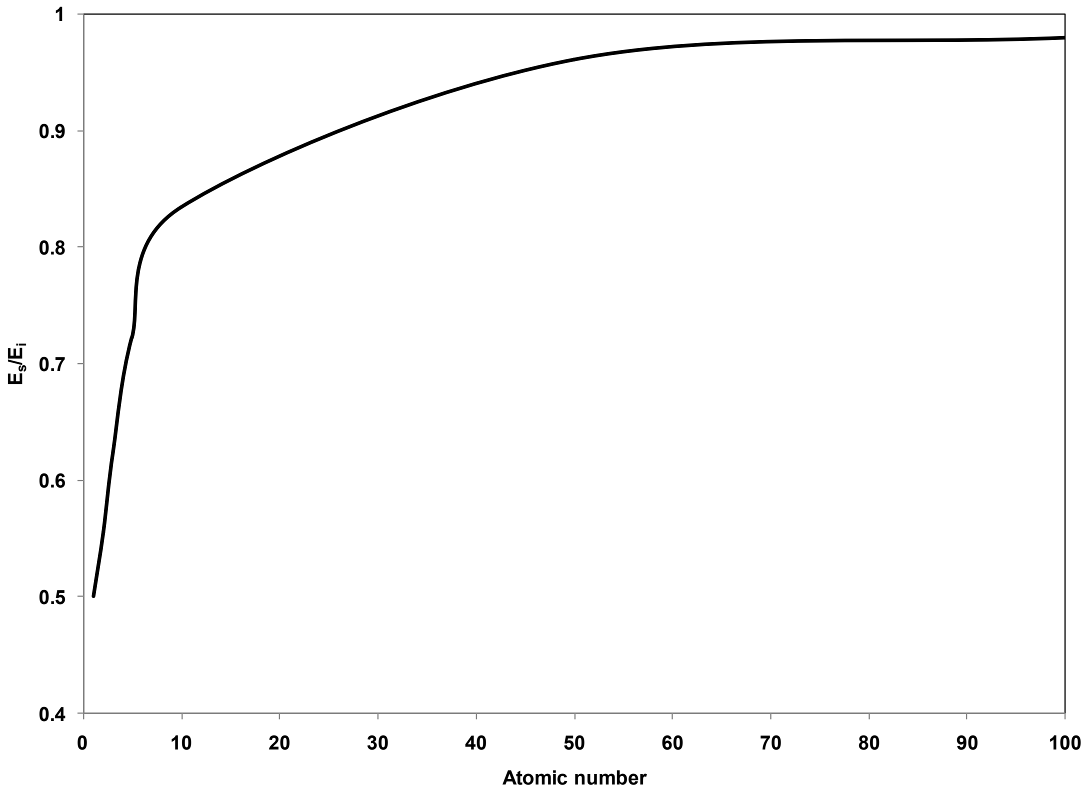

Fig 1. Ratio of energies of scattered neutrons to incident neutrons

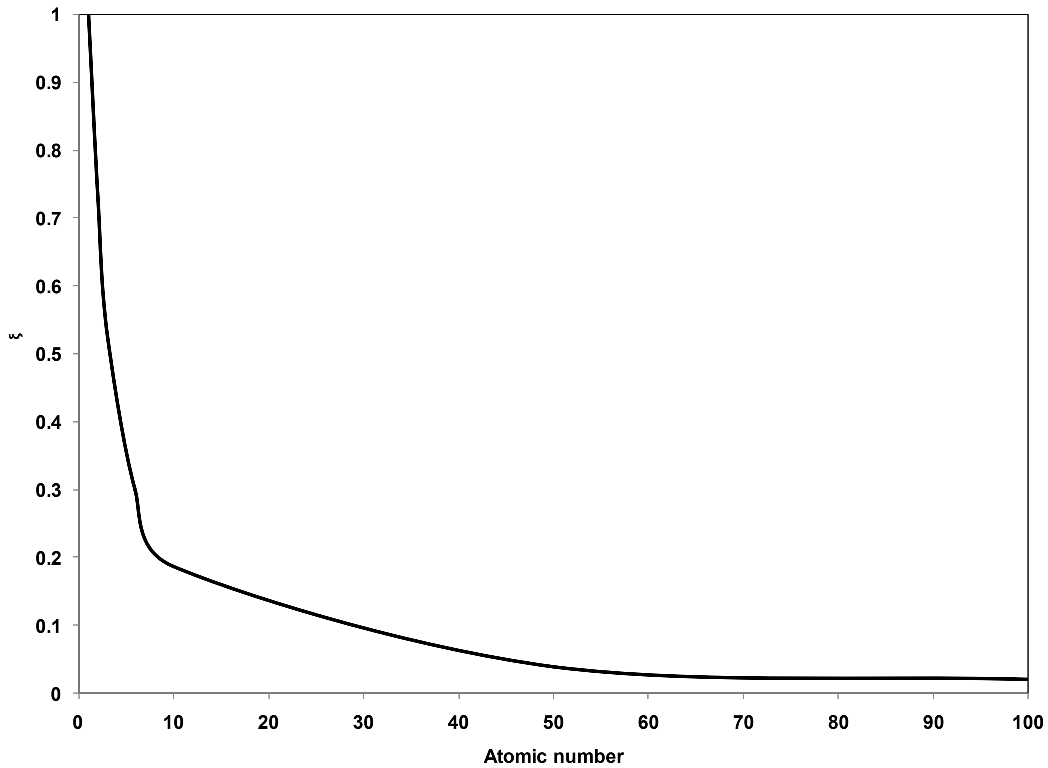

Fig 2. Mean logarithmic energy decrement as a function of atomic number

If E_{high} and $E_{thermal}$ are the kinetic energies of high energy neutron and thermal neutron respectively, then

$$\frac{E_{high}}{E_{thermal}} = \frac{E_{high}}{E_1} \cdot \frac{E_1}{E_2} \cdot \frac{E_2}{E_3} \ldots\ldots \frac{E_{n-1}}{E_{thermal}} \tag{6}$$

$$\frac{E_{high}}{E_{thermal}} = e^{\xi} . e^{\xi} . e^{\xi} \ldots e^{\xi} = e^{n\xi} \tag{7}$$

The following example shows the calculation of nuclear of collisions for a typical case

Example 1: Determine the number of collisions required for thermalization for the following case.

Data: Energy of incident neutron = E_{high} = 1 MeV

Energy of thermal neutron = $E_{thermal}$ = 0.0253 MeV

Moderator: Heavy water

ξ = 0.509

Solution:

Using Eq. (7)

$$\frac{1e6}{0.0253} = e^{0.509n} \tag{8}$$

Solving Eq. (8), we get n =34

For light water (ξ = 0.920) and graphite (ξ = 0.158) as moderators, the numbers of collisions required for reduction of neutron energy from 1 MeV to 0.0253 eV are 19 and 111 respectively (calculated using equation 7).

1.1 Moderating ratio

It may be recalled that the nuclear cross sections represent the probability of various nuclear reactions. When neutron interacts with a nucleus, one of the following can happen: elastic scattering, inelastic scattering, neutron capture and fission.

As we have seen earlier, the slowing down of neutrons is due to the elastic scattering of neutron by the nucleus of moderator. If the capture cross section of moderator (σ_γ) is high, most of the neutrons will be absorbed by it, leading to lower moderation or lower availability of thermal neutrons.

Hence a higher ratio of scattering to capture cross sections (σ_{el} /σ_γ) is desirable for effective moderation. Combining this ratio with mean logarithmic energy decrement

(ξ), 'moderating ratio' can be calculated which can be used as a criterion for comparison of different moderators.

$$\text{Moderating ratio} = \frac{\xi\sigma_{el}}{\sigma_\gamma} \tag{9}$$

Moderating ratio will be high if either of (ξ) or ($\sigma_{el}/\sigma_\gamma$) is higher. The following table gives the values of ξ, and $\sigma_{el}/\sigma_\gamma$ of some common moderators.

Table 1. Moderating ratio for common moderators. Note that the cross sections are corresponding to the neutron energy of 0.0253 eV (thermal neutron)

Moderator	ξ	σ_{el} (b)	σ_γ (b)	$\sigma_{el}/\sigma_\gamma$	Moderating ratio	n
Light water	0.920	25.47	0.33	77.17	71	19
Heavy water	0.509	5.57	0.0005	11139.49	5670	34
Graphite	0.128	5.25	0.0035	1500	192	111

Though light water has the highest ξ and σ_{el} among the three moderators shown, its moderating ratio is low due to its relatively higher capture cross section. Heavy water has the highest moderating ratio owing to its lowest cross section for neutron capture. Graphite, despite possessing the lowest ξ and σ_{el}, fairs better than light water due to its lower σ_γ compared to that of light water.

The relative advantages and disadvantages of heavy water and light water, the common moderators in Indian reactors are as follows:

Table 2. Relative advantages and disadvantages of light and heavy water as moderator

Moderator	Advantages	Disadvantages
Heavy water	High moderating ratio and hence can be used with natural uranium fuel	More expensive; Requires a core of larger diameter to facilitate 34 collisions between a neutron and the moderator
Light water	Less expensive; Requires a core of relatively smaller diameter as only 19 collisions are required for moderation	Can be used only with enriched uranium fuel

2 Moderator System in Pressurized Heavy Water Reactor

Coolant and moderator are not separated in light water reactors. However, despite using heavy water as both moderator and coolant, they are housed in separate compartments in a pressurized heavy water reactor. Heavy water as coolant flows inside the pressure tubes, while the calandria is immersed in the moderator. The moderator is not directly heated by heat transfer from fuel. Instead, moderator is heated due to the energy lost by neutrons during their slow down. The energy of prompt gamma radiation is also deposited in the moderator. It may be recalled that about 5 % of 200 MeV of recoverable energy from fission is released in the moderator. Hence the moderator needs to be cooled to maintain its temperature, to prevent vaporization. Typically, the moderator is maintained between 60 °C and 80 °C. The moderator system is designed to maintain the temperature of moderator within this range. A schematic diagram of moderator system with pumps, valves and heat exchangers is shown in Figure 3.

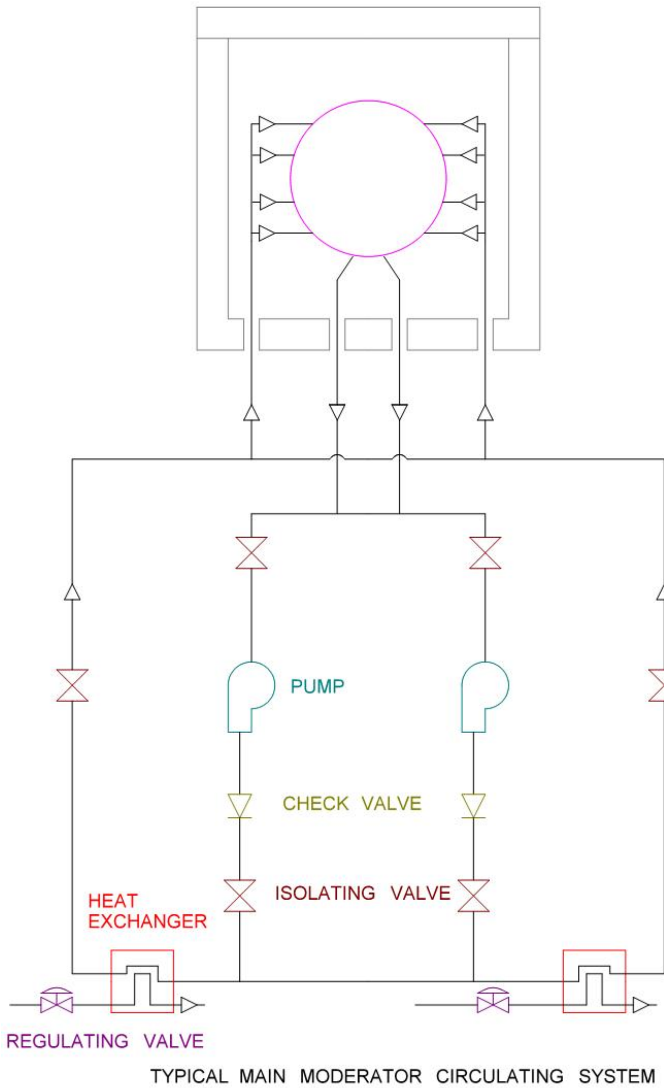

Fig 3. Moderator system of PHWR (Redrawn from Ref. [2])

Calandria has outlets at the bottom for the removal of moderator. The inlets for moderator are provided on the sides of calandria as shown in Figure 3. Moderator pumps are used to pump the moderator out from calandria and pass them through heat exchangers. Moderator is cooled in these heat exchangers using light water supplied for this purpose. The flow rate of light water is controlled depending upon the temperature of moderator.

Two heat exchangers are shown in Figure 3. Each heat exchanger is provided with an isolation valve that can be used to disconnect that particular heat exchanger from the system, for maintenance. In such cases, one heat exchanger can be used to maintain the temperature of moderator. The presence of check valves in the line ensure that there is no return flow, in case of failure of moderator pump.

3 References/Additional Reading

1. David Bodansky, Nuclear Energy: Principles, Practices, and Prospects, 2/e, Springer-Verlag, USA, 2004 (Chapter 7)
2. https://canteach.candu.org/Content%20Library/20040712.pdf