FUEL, MODERATOR, AND REACTOR ARRANGEMENT

OBJECTIVES

At the conclusion of this lesson the trainee will be able to:

1. Explain the purpose of a moderator.
2. Sketch the basic arrangement of fuel and moderator in a CANDU reactor and explain why this arrangement is desirable.
3. State the basic differences between fresh and equilibrium fuel.
4. Compare the moderating properties of heavy water, light water and graphite.

FUEL, MODERATOR, AND REACTOR MANAGEMENT

An assemblage of material which will just give a self-sustaining chain reaction is called a critical mass. If we had a small pile of pure U-235 and initiated fission, many of the neutrons would escape before they could cause further fissions. Thus the chain reaction would die away. As more U-235 is added to the pile, fewer neutrons would escape before causing fission and at some point the pile would support a self-sustaining chain reaction. A pile of that size is the critical mass of U-235.

It is important to note that natural uranium (0.7% U-235) cannot be made critical without the help of a moderator. Too many of the neutrons are absorbed by the resonance peaks in U-238 and are thus unavailable to cause fission.

In order to obtain a self-sustaining chain reaction with natural uranium it is necessary to take the fission neutrons away from the fuel, slow them down to thermal energy then return them to the fuel. By using this process the neutrons are:

1. Away from the U-238 when they have slowed to the resonance absorption energies, and

2. They return to the fuel at thermal energy where they are far more likely to be absorbed by U-235 and cause fission.

Moderator

The function of the moderator is to slow down the fission neutrons without absorbing them. In order to perform this function adequately a moderator must:

1. Thermalize the neutrons in as few collisions as possible over a short distance,

2. Not absorb too many of the neutrons.

Neutrons lose most of their energy by elastic collisions with other nuclei. Elastic scattering with light nuclei is a more efficient method of moderation than elastic scattering with heavy nuclei. It takes an average of only 18 collisions to thermalize a neutron in pure hydrogen but it takes 2172 collisions to thermalize the same neutron in U-238. Thus only light nuclei are considered suitable as moderators.

The second point is low absorption. Boron ($^{10}_{5}B$) could thermalize a neutron in $\approx$90 collisions but it has an absorption cross-section of 3840 barns and would therefore absorb most of the neutrons it thermalized.

As a result of these nuclear considerations and other economic and engineering considerations, only three moderators are considered suitable for thermal reactors; light water (H_2O), heavy water (D_2O) and graphite (C). Table 5.1 summarizes the properties of each.

Moderator	Average Number of Collisions to Thermalize	σ_s (barns)	σ_a (barns)
H_2O	20	103	0.664
D_2O	36	13.6	0.001
C	115	4.8	0.0034

Table 5.1

Clearly light water will thermalize a neutron faster than either heavy water or graphite (higher scattering cross-section coupled with fewer collisions to thermalization). However, light water's absorption cross-section is 664 times that of heavy water and 195 times that of graphite. Due to light water's neutron absorption, it is impossible to obtain a self-sustaining chain reaction with natural uranium fuel and a light water moderator. Light water moderated reactors must use 2 to 3% enriched fuel. (Uranium in which the percentage of U-235 has been increased from 0.7% to 2 or 3%.)

Most reactor designs, including the CANDU, use UO_2 rather than uranium metal for fuel. Ceramic fuel (UO_2) has excellent corrosion resistance and is very stable in a radiation environment, making it a good choice for reactor fuel. However, it is impossible to obtain a critical mass of unenriched UO_2 with a graphite moderator. Only heavy water is suitable as a moderator for a reactor using unenriched UO_2.

Fresh Fuel and Equilibrium Fuelling

When a reactor is first fuelled the fuel is called fresh fuel. This initial fuel load will operate the reactor for about 6 months after which we remove and replace a few fuel bundles each day. This state is called equilibrium fuelling.

Radical changes occur in the composition of the fuel between the fresh and equilibrium conditions. The most significant are the depletion of the U-235, mostly by fission, the buildup of fission products and the buildup of Pu-239 (a fissile fuel) by the following scheme:

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U + \gamma$$

$$^{239}_{92}U \rightarrow ^{239}_{93}Np + \beta + \gamma \qquad (T_{\frac{1}{2}} = 23.5 \text{ m})$$

$$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + \beta + \gamma \qquad (T_{\frac{1}{2}} = 2.35 \text{ d})$$

Fresh fuel contains 0.7% U-235 and no Pu-239. By the time fuel is removed from the reactor the U-235 is depleted to near 0.2% and there is an approximately equal amount of Pu-239. The fissioning of Plutonium provides a significant portion of the power produced by a CANDU reactor.

Each atom that fissions produces two new atoms so the fission products build up to a concentration just over 1%. The content of U-238 in the fuel changes very little.

Reactor Arrangement

Figure 7.1 and 7.2 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 resonance absorption occurs. The neutrons are then thermalized in the moderator before re-entering the fuel. This arrangement accomplishes two goals:

1. slowing down neutrons to thermal energy where the fission cross-section is significantly higher, and

2. minimizing neutron captures by:

   a) keeping the neutrons away from the U-238 while they are passing through resonance energy.

   b) returning the neutrons quickly to the fuel to reduce absorption in the moderator.

The channel spacing shown in Figure 7.2 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 <u>only</u> be made critical in heavy water in an arrangement similar to the one used. Thus there is no chance of a criticality accident in the handling or storage of CANDU fuel.

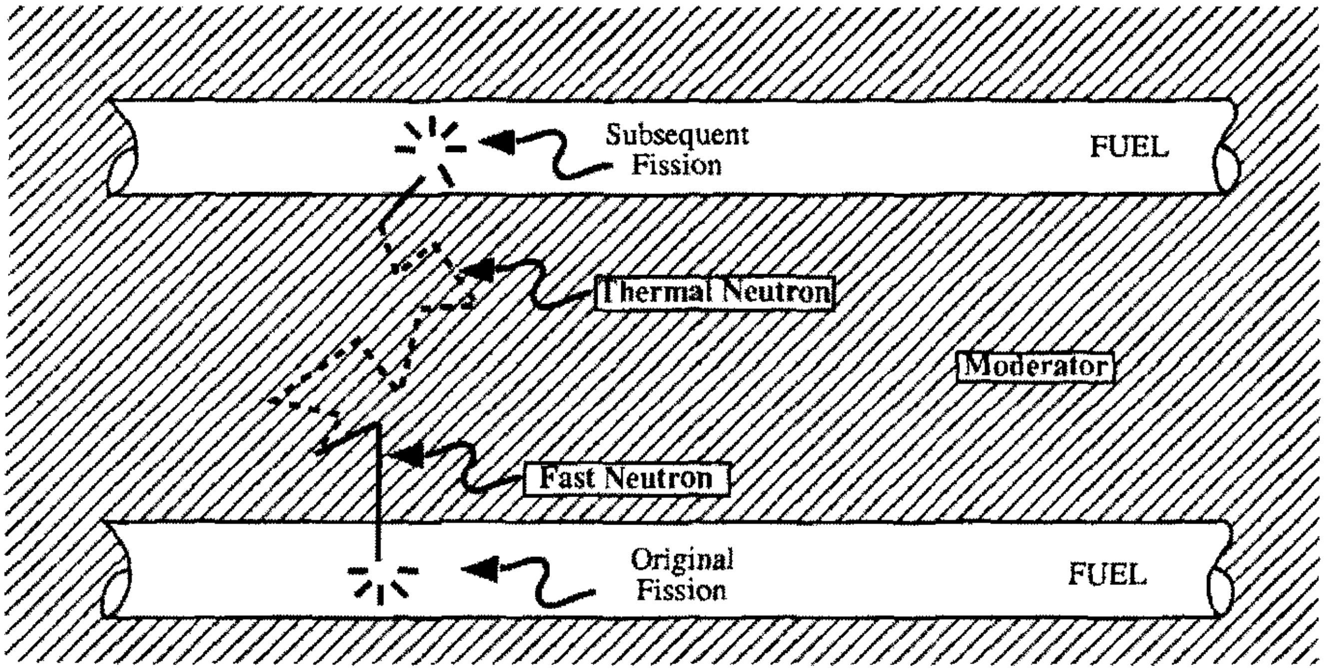

Figure 7.1: Axial Reactor Arrangement

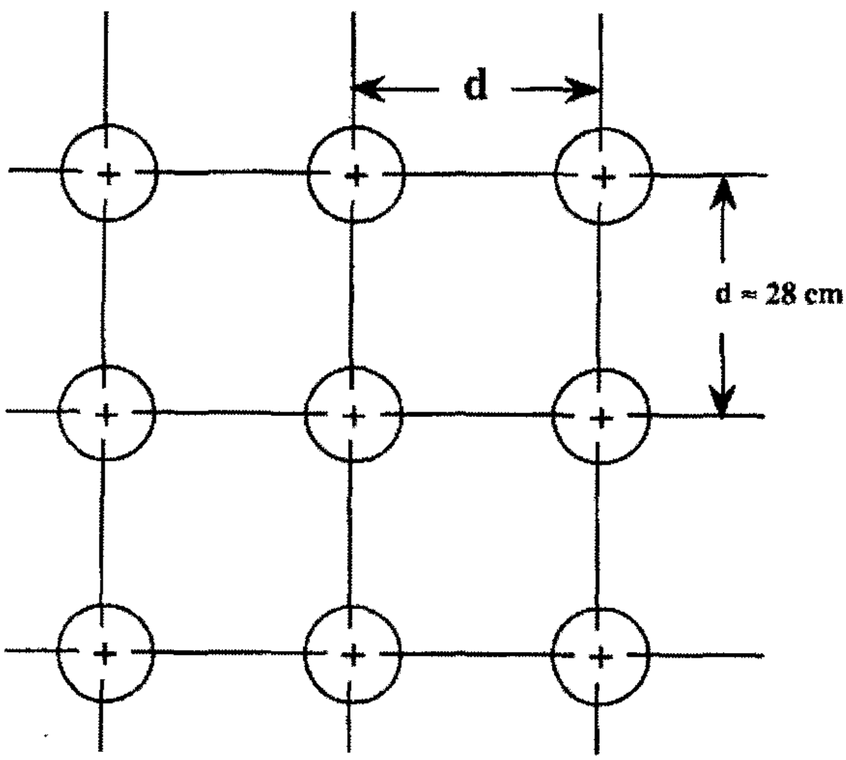

Figure 7.2: Radial Fuel Arrangement

ASSIGNMENT

1. Describe the arrangement of the fuel and moderator in a CANDU reactor.

2. Explain why heavy water (D_2O) is a better choice as a moderator than light water (H_2O).

3. Explain the differences between fresh and equilibrium fuel.

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