8 Fuel, Moderator, and Reactor Management

An aggregate of material that 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 neutrons would escape before they could cause further fissions. The chain reaction would die away. For a larger pile, fewer neutrons escape before causing fission and for some particular size, the pile supports a self-sustaining chain reaction. A pile of that size contains the critical mass of U-235.

It is an important feature of natural uranium (0.7% U-235, 99.3% U-238) that it cannot be made critical by itself, no matter how large a pile is assembled. The resonance peaks in U-238 absorb so many of the neutrons that too few neutrons remain to sustain a chain reaction.

To obtain a self-sustaining chain reaction with natural uranium the neutrons must be slowed to thermal energy (to increase the probability of fission) away from the fuel (to limit U-238 absorption). The neutrons move in random directions, so we cannot directly control this. However, by concentrating the fuel in channels separated by an effective moderator, fewer neutrons are exposed to resonance capture and there are high odds of thermalization. By using this process, most of the neutrons are:

1. Away from the U-238 while slowing through the energy range of the U-238 resonances, and

2. Far more likely, once thermalized, to be absorbed by U-235 and cause fission.

8.1 Moderator

CANDU reactors, like most other power reactors in the world, are thermal reactors. That is, they use thermal neutrons to cause fissions. For the reactor to operate, the fast neutrons released during fission must be slowed to thermal energies before they will cause another fission.

The function of the moderator is to slow the fission neutrons without absorbing them. To perform this function effectively 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.

Fast neutrons lose their energy mainly by elastic collisions with other nuclei. Elastic scattering with light nuclei is more effective than elastic scattering with heavy nuclei. It takes an average of 18 collisions to thermalize a neutron in pure hydrogen but 2172 collisions to thermalize the same neutron in U-238. Thus, only light nuclei are suitable as moderators.

The second point is low absorption. Boron-10 could thermalize a neutron in ~90 collisions but, with an absorption cross-section of 3840 barns it would absorb the neutrons it thermalized.

Because of these nuclear considerations and other engineering and economic considerations, only three moderators are suitable for thermal reactors*: light water (H_20), heavy water (D_2O) and graphite (C). Table 8.1 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	0.0010
C	115	4.8	0.0034

Table 8.1

Clearly, light water thermalizes 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. Heavy water is the only possible moderator for a reactor using natural uranium UO_2 fuel.

8.2 Fresh Fuel and Equilibrium Fuelling

When a reactor is first fuelled, the fuel is called fresh fuel. This initial fuel load is good for about 6 months. After this we remove and replace a few fuel bundles each day, a state called equilibrium fuelling.

Radical changes occur in the composition of the fuel between the fresh and equilibrium conditions. Three significant changes are the depletion of the U-235, mostly by fission, the build-up of fission products, and the build-up of Pu-239 (a fissile fuel) by the following nuclear processes:

$$ {}^{1}_{0}n + {}^{238}_{92}U \rightarrow {}^{239}_{92}U + \gamma \qquad \text{(radiative capture)} $$

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

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

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 a similar amount of Pu-239. Plutonium fission 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 over 1%. The content of U-238 in the fuel changes very little.

8.3 Reactor Arrangement

Figures 8.1 and 8.2 show the axial and radial arrangement of the fuel in the moderator. This arrangement permits most of the fast neutrons from fission to leave the fuel and enter the moderator before significant resonance absorption occurs. The moderator thermalizes the neutrons away from the U-238 in the fuel and most neutrons re-enter the fuel as thermal neutrons. This arrangement accomplishes two goals:

1. slowing the neutrons to thermal energy, which significantly increases the fission cross-section,

2. minimizing neutron captures by:

   a) Keeping the U-238 away from most of the neutrons while they are passing through the resonance energy range.

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

The channel spacing shown in Figure 8.2 is very important and is carefully chosen for CANDU reactors. Any significant increase or decrease in this spacing decreases the probability of sustaining a chain reaction.

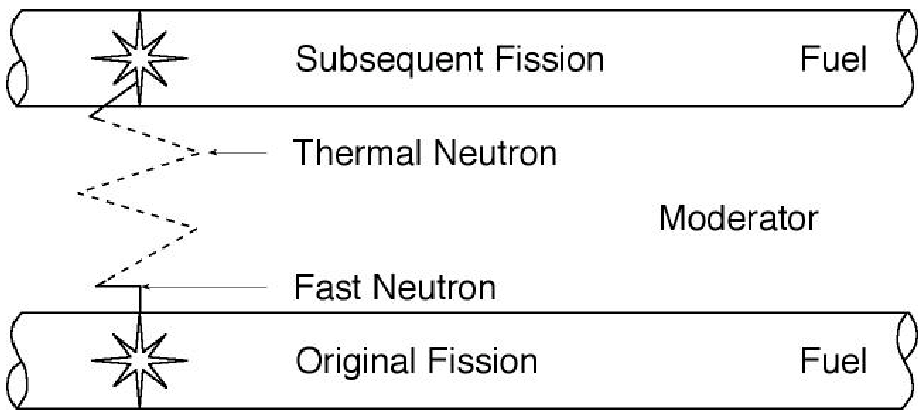

Figure 8.1
Axial Reactor Arrangement

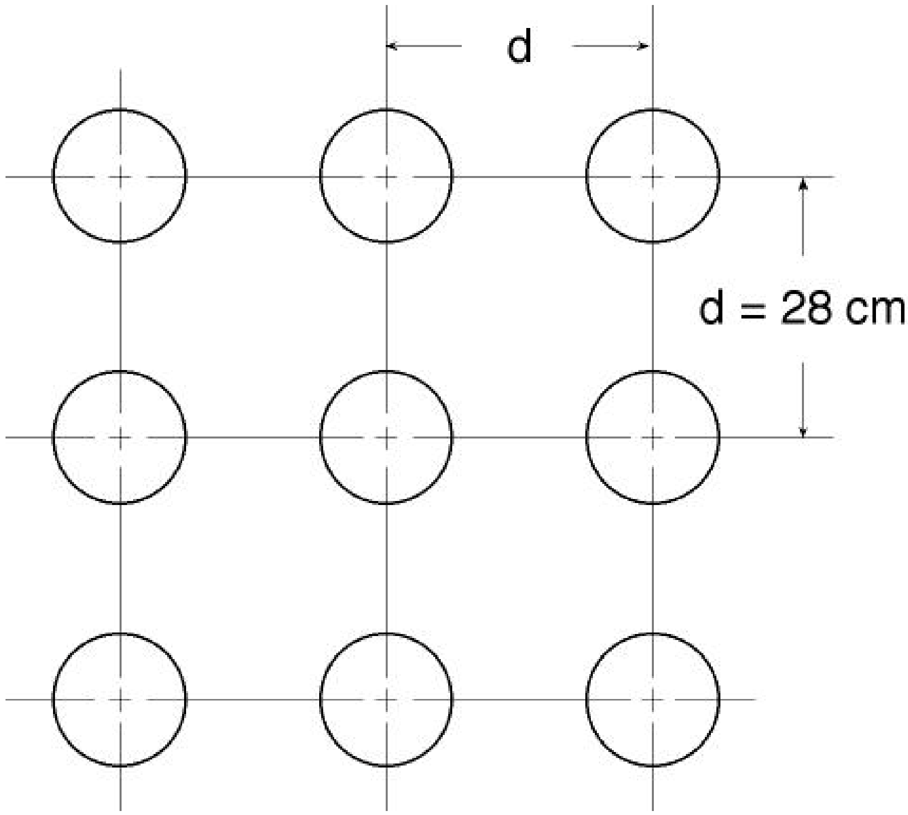

Figure 8.2
Radial Fuel Arrangement

An important safety feature of CANDU fuel is that it can constitute a critical mass only in heavy water in an arrangement similar to the one used. There is no chance of a criticality accident in the handling or storage of CANDU fuel provided storage and handling of D_2O and fuel occur in physically separated locations. New fuel is stored in a configuration that does not support criticality, in an area with good drainage, separated from any D_2O

8.4 Summary of Key Ideas

- Sufficient mass of U-235 would become critical on its own.
- No amount of natural Uranium can achieve a critical mass because of absorption in U-238.
- Neutrons must be away from the fuel when they are slowed so they do not undergo resonance capture by U-238.

- Materials suitable for moderators are H_2O, D_2O and carbon. D_2O is the best moderator, it has good slowing down properties and a very low absorption cross section.

- During the initial stages of irradiation, Pu-239 builds up in the fuel. Pu-239, like U-235 is fissile and produces significant amounts of power in the reactor.

- In a CANDU reactor the fuel is placed in channels about 4 meters long (in the reactor).

- The channels are arranged in a square lattice spaced about 28 cm from center to center.

8.5 Assignment

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

2. Explain why the arrangement described in question one is important.

3. Explain why heavy water (D_2O) is a better choice as a moderator than light water (H_2O). Can you suggest any disadvantages?

4. Describe the differences between fresh and equilibrium fuel.

5. How do you expect your answer to question one would be affected for:

   a. a light water moderated reactor with enriched UO_2 fuel,

   b. a graphite moderated reactor with enriched UO_2 fuel.

6. Suggest reasons why the fuel in the spent fuel bay will not go critical.