Reactor Boiler and Auxiliaries - Course 133

MODERATOR REQUIREMENTS

The advantages of slowing down and thermalizing neutrons before allowing them to cause fission, were considered during the discussions of reactor classifications. It was seen that the fission cross-section for thermal neutrons is so much greater than the radiative capture cross-section that the high fuel enrichment, required in fast reactors, is no longer necessary. In heterogeneous thermal reactor systems, little or no enrichment is required.

The slowing down of fission neutrons to thermal energies takes place in two stages:-

(a) Inelastic scattering by the heavier nuclei, such as U-238, which are already present in the fuel. During this stage the neutron energy is only reduced to about 0.1 Mev and so, further slowing down of the neutrons is required.

(b) Further slowing down of neutrons, below 0.1 Mev, occurs by elastic scattering of the neutrons by the lighter nuclei of the moderator.

The basic requirements of moderators will now be discussed at greater length and the suitability of substances, as moderators, will be considered.

Nuclear Considerations

The first requirement of a moderator is that it should slow down neutrons, to thermal energies, quickly. The energy loss at each collision, between the neutron and moderator nuclei, should be as large as possible. This decreases the resonance capture and increases the probability of fission. It also decreases the chances of radiative capture generally. It has already been established that the lighter nuclei are the most effective in slowing down neutrons rapidly. As may be seen, from Table 1, which follows later in the lesson, a neutron would be slowed down to thermal energies after 18 collisions with hydrogen nuclei whereas it would require 25 collisions with deuterium nuclei, 43 with helium, 105 with boron and 114 with carbon.

The effectiveness of a material in slowing down neutrons, by elastic scattering, is measured by the Average Logarithmic Energy Decrement (ξ). This quantity, ξ, is the average decrease in the natural logarithm of the neutron energy per collision.

The number of collisions (N) required to thermalize a fission neutron is then given by $N = \frac{18.2}{\xi}$

This is not the only factor that determines the suitability of a material as a moderator. Consideration must also be given to the following:-

(a) A nucleus may be very effective in slowing down a neutron when a neutron collides with it, but this is of no value at all unless these scattering collisions take place. This leads to two further requirements, which are:-

(i) The moderator cannot be a gas since the density of the nuclei in a gas is much too small for frequent scattering collisions to take place. This means that the two best substances, hydrogen and deuterium gases, cannot be used as moderators. They are available, in liquid form, combined with oxygen, in water (H_2O) and heavy water (D_2O). So the moderator must be a solid or a liquid.

(ii) The moderator substance must have a large scattering cross-section to ensure frequent scattering collisions.

The overall efficiency of a substance, for slowing down neutrons, is measured by the SLOWING DOWN POWER, ($\xi \Sigma_s$). This slowing down power takes the frequency of the scattering collisions into consideration as well as the energy loss at each collision. From the table, it is clear that light water (H_2O) is the most effective slowing down medium followed by beryllium, heavy water (D_2O), carbon and boron. The slowing down power of the gas, helium, is shown for comparison.

(b) Not only must the moderator be effective as a slowing down medium but it must, also, have a small capture cross-section. Neutrons are slowed down to decrease radiative captures compared to fission captures and, therefore, the whole object of moderation would be defeated if the moderator nuclei themselves, capture neutrons.

The MODERATING RATIO, $\frac{\xi \Sigma_s}{\Sigma_a}$ is the ratio of the slowing down power to the absorption cross-section. This quantity is, therefore, a better indication of the overall suitability of a material as a moderator.

TABLE 1

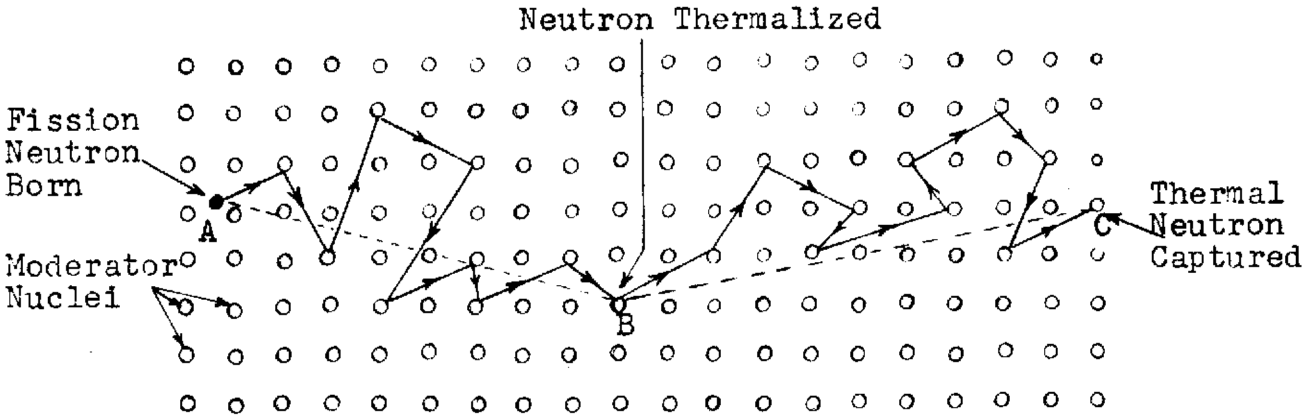
Material	Number of Collisions to Thermalize	Slowing-down Power	Moderating Ratio
Hydrogen	18		
Deuterium	25		
Beryllium	86	0.176	159
Boron	105	0.06	0.0009
Carbon	114	0.064	170
Helium	43	1.6×10^{-5}	83
H_2O	19	1.53	72
D_2O	35	0.170	21,000
Zinconium Hydride		0.8	56
Terphenyl		0.73	80

The above table shows that, although H_2O has the highest slowing down power, its moderating ratio is lower than that of carbon and beryllium. The moderating ratio of H_2O is so low that it can not be used as a moderator to sustain a chain reaction unless it is used with enriched fuel. The superiority of D_2O, however, is very apparent and it can be seen why D_2O is the only moderator which could be used in a natural uranium homogeneous system.

(c) The substance used as a moderator must be very pure. It is usually used, in a reactor, in larger amounts than any other material e.g. the volume of carbon, in a graphite moderated reactor, is 70 - 80 times that of the fuel. A very small amount of impurity in a moderator can substantially increase its capture cross-section. The addition of 1 boron atom to every million graphite atoms would increase the capture cross-section of graphite by 25%.

For the same reason the isotopic purity of D_2O must be kept high. The addition of 0.25% H_2O to pure D_2O more than doubles the capture cross-section. The isotopic purity of D_2O is, therefore, kept at between 99.75% and 99.8% D_2O by weight. A 1% decrease in the isotopic purity of the NPD heavy water would cause a 25mk decrease in the reactivity. This would result in a loss of fuel burnup estimated to be worth $175,000 per year.

Two other quantities that are closely connected with the moderator properties are the SLOWING DOWN LENGTH and the DIFFUSION LENGTH of the neutrons. As shown in Figure 1 a neutron travels an erratic zig-zag path from A to B while it is being thermalized. The slowing down length, L_s, is a measure of the "crow flight" or direct distance AB travelled by the neutron while being thermalized.



<u>Fig. 1</u>

$$L_s^2 = \frac{1}{6}\ \text{(average value of } AB^2\text{)}$$

After being thermalized at B, the thermal neutron continues to move or diffuse through the reactor before being captured. It follows the zig-zag path BC. The diffusion length, L, of a thermal neutron is a measure of the "crow flight" distance BC travelled by the thermalized neutron before being captured.

$$L^2 = \frac{1}{6}\ \text{(average value of } BC^2\text{)}$$

The slowing down length determines the extent to which fast neutrons escape from the reactor and it is, therefore, a factor in determining the critical size of the reactor. It also determines how much moderator is required between fuel channels to thermalize the neutrons and keep p, the resonance escape probability, as high as possible, i.e. it determines the reactor pitch. Ideally, then, L_s should be as small as possible.

The diffusion length determines how fast the thermal neutrons are lost by capture. It also determines the extent to which thermal neutrons escape or leak out of the reactor but since the majority of thermal neutrons are captured in the fuel, or in core material the former factor is the more important of the two. Therefore, L, should be as large as possible in order to have a high value of f, the thermal utilization factor.

The slowing down lengths and the diffusion lengths for possible moderator materials are given in the following table.

TABLE 2

Material	L(cm)	L_s(cm)
Water (H_2O)	2.8	5.6
Heavy Water (99.84% D_2O)	100	11
Beryllium (ρ = 1.85)	21	9.2
Beryllium Oxide (ρ = 3.0)	29	10
Graphite (ρ = 1.6)	64	19

The temperature of the moderator may well affect the values of L, L_s and other nuclear parameters. An increase in temperature causes a decrease in density which, in turn, causes an increase in both L and L_s. This tends to increase neutron leakage and to increase the value of f. An increase in temperature also causes an increase in the molecular energy so that the thermal energy of the neutrons will be increased. Thus the energy of the neutrons entering the fuel will be higher. In uranium fuel this would decrease the U-235 fission captures and increase the U-238 resonance captures i.e. decrease p. As plutonium builds up in the fuel the increase in neutron energy increase plutonium fission captures. Neutron economy is therefore, improved by keeping the moderator at a moderate temperature, particularly with fresh fuel. This is of particular significance in heavy water moderated reactors where neutron economy is of such importance.

Non-nuclear Considerations

Numerous chemical and physical properties of possible moderator materials must be considered in addition to the nuclear properties considered above. The following are some of the more important considerations:-

(a) The material should be chemically inert to its environment. In the case of a liquid it should not cause corrosion of the containing system nor cause scale formation. Corrosion products can cause flow reductions and they also become radioactive and may lead to contamination.

Solid moderators should not oxidize, even at elevated temperatures, nor should they react with the heat transport fluid.

(b) Liquid moderators should have as high a boiling point as possible particularly if a common moderator -- heat transport fluid is being used. Little or no pressurization is then required.

Solid moderators must have high melting points.

(c) Where solid moderators are also used as structural materials they should have good, thermal conductivities, low thermal expansion, high tensile and compressive strengths and have good resistance to thermal shock and creep.

These desirable characteristics must be maintained at elevated temperatures.

(d) Materials used as moderators should be non-toxic since additional costs are involved in the production, fabrication and containment of toxic materials.

(e) The material should be resistant to radiation damage. In particular, solids should not distort or expand under irradiation nor should their desirable physical and mechanical properties be affected.

Radiation should not cause dissociation, cross-linking, tar or coke formation or any excessive changes in the desirable physical properties of liquids.

(f) It must be readily available at a reasonable cost.

ASSIGNMENT

1. (a) Of what significance are the "Average Logarithmic Energy Decrement", the "Slowing Down Power" and the "Moderating Ratio" in determining the suitability of a material as a moderator?

   (b) Helium gas requires only 43 collisions to thermalize a neutron compared with 114 with carbon. Why is helium gas not considered as a moderator?

   (c) The slowing down power of boron is 0.06 whereas that of carbon is 0.064. Which would be considered the better moderator and why?

2. (a) Why is the purity of a moderator material such an important factor?

   (b) Of what significance is this factor in the choice of the graphite used in a reactor?

3. (a) Of what significance are the "Slowing Down Length" and the "Diffusion Length" in reactor design and, ideally, what values should they have?

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