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## REACTIVITY COEFFICIENTS

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*Changes in the physical properties of the materials in the reactor will result in changes in the reactivity. Reactivity coefficients are useful in quantifying the reactivity change that will occur due to the change in a physical property such as the temperature of the moderator or fuel.*

- EO 2.1**      **EXPLAIN** the conditions of over moderation and under moderation.
- EO 2.2**      **EXPLAIN** why many reactors are designed to be operated in an under moderated condition.
- EO 2.3**      **STATE** the effect that a change in moderator temperature will have on the moderator to fuel ratio.
- EO 2.4**      **DEFINE** the temperature coefficient of reactivity.
- EO 2.5**      **EXPLAIN** why a negative temperature coefficient of reactivity is desirable.
- EO 2.6**      **EXPLAIN** why the fuel temperature coefficient is more effective than the moderator temperature coefficient in terminating a rapid power rise.
- EO 2.7**      **EXPLAIN** the concept of Doppler broadening of resonance absorption peaks.
- EO 2.8**      **LIST** two nuclides that are present in some types of reactor fuel assemblies that have significant resonance absorption peaks.
- EO 2.9**      **DEFINE** the pressure coefficient of reactivity.
- EO 2.10**     **EXPLAIN** why the pressure coefficient of reactivity is usually negligible in a reactor cooled and moderated by a subcooled liquid.
- EO 2.11**     **DEFINE** the void coefficient of reactivity.
- EO 2.12**     **IDENTIFY** the moderator conditions under which the void coefficient of reactivity becomes significant.
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## **Moderator Effects**

As discussed in the previous module, a moderator possesses specific desirable characteristics.

- (a) large neutron scattering cross section
- (b) low neutron absorption cross section
- (c) large neutron energy loss per collision

With the exception of the Liquid Metal Fast Breeder Reactor (LMFBR), the remaining major reactor types that are currently employed use moderating materials to reduce fission neutron energies to the thermal range. Light moderators (composed of light nuclei) are found to be more effective than heavy moderators because the light moderator removes more energy per collision than a heavy moderator. Therefore, the neutrons reach thermal energy more rapidly and they are less likely to be lost through resonance absorption.

As discussed in a previous module, the ability of a given material to slow down neutrons is referred to as the macroscopic slowing down power (MSDP) and is defined as the product of the logarithmic energy decrement per collision ( $\xi$ ) times the macroscopic scattering cross section for neutrons as follows.

$$\text{MSDP} = \xi \Sigma_s$$

Macroscopic slowing down power indicates how rapidly slowing down occurs in the material in question, but it does not completely define 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 is a poor moderator. It is a poor moderator because of its high probability of absorbing neutrons, and may be accounted for by dividing the macroscopic slowing down power by the macroscopic absorption cross section. This relationship is called the moderating ratio (MR).

$$\text{MR} = \frac{\xi \Sigma_s}{\Sigma_a}$$

The moderating ratio is merely the ratio of slowing down power to the macroscopic absorption cross section. The higher the moderating ratio, the more effectively the material performs as a moderator.

Another ratio, the *moderator-to-fuel ratio* ( $N^m/N^u$ ), is very important in the discussion of moderators. As the reactor designer increases the amount of moderator in the core (that is,  $N^m/N^u$  increases), neutron leakage decreases. Neutron absorption in the moderator ( $\Sigma_a^m$ ) increases and causes a decrease in the thermal utilization factor. Having insufficient moderator in the core (that is,  $N^m/N^u$  decreases) causes an increase in slowing down time and results in a greater loss of neutrons by resonance absorption. This also causes an increase in neutron leakage. The effects of varying the moderator-to-fuel ratio on the thermal utilization factor and the resonance probability are shown in Figure 2.

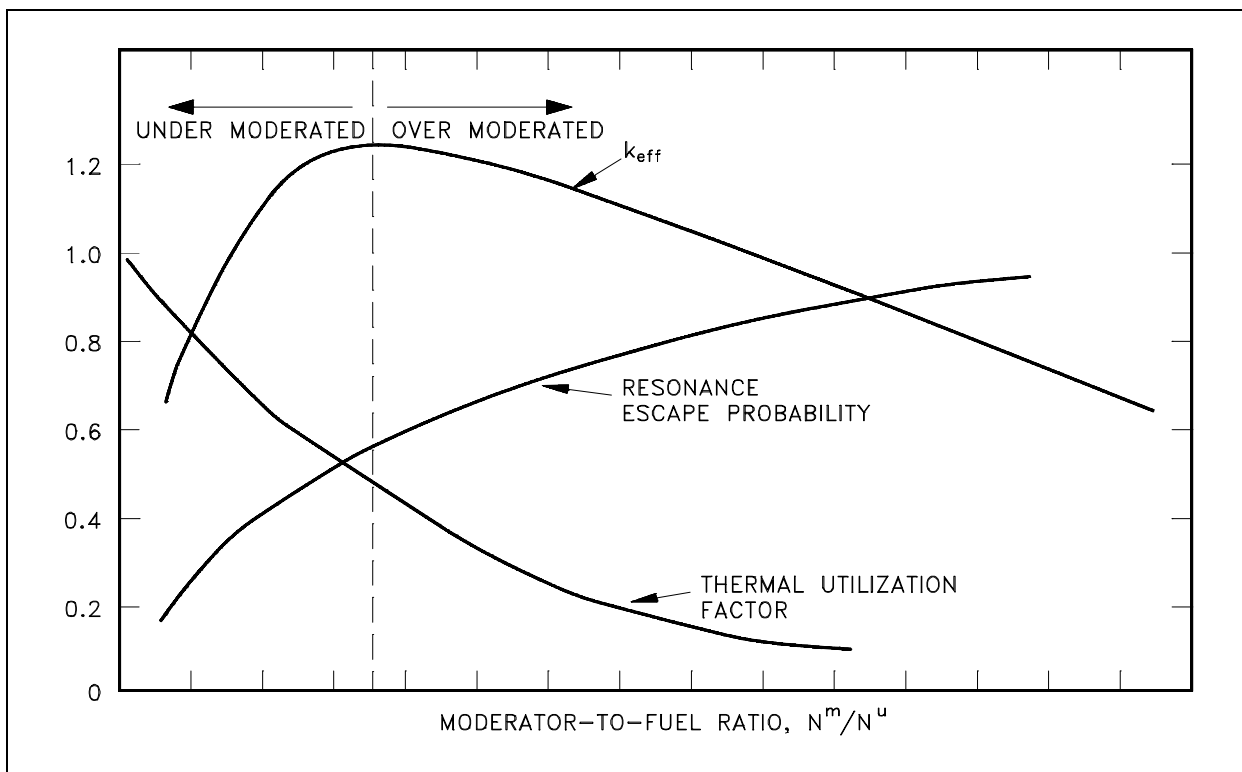


Figure 2 Effects of Over and Under Moderation on  $k_{eff}$

Because the moderator-to-fuel ratio affects the thermal utilization factor and the resonance escape probability, it also affects  $k_{eff}$ . The remaining factors in the six factor formula are also affected by the moderator-to-fuel ratio, but to a lesser extent than  $f$  and  $p$ . As illustrated in Figure 2, which is applicable to a large core fueled with low-enriched fuel, there is an optimum point above which increasing the moderator-to-fuel ratio decreases  $k_{eff}$  due to the dominance of the decreasing thermal utilization factor. Below this point, a decrease in the moderator-to-fuel ratio decreases  $k_{eff}$  due to the dominance of the increased resonance absorption in the fuel. If the ratio is above this point, the core is said to be over moderated, and if the ratio is below this point, the core is said to be under moderated.

In practice, water-moderated reactors are designed with a moderator-to-fuel ratio so that the reactor is operated in an under moderated condition. The reason that some reactors are designed to be under moderated is if the reactor were over moderated, an increase in temperature would decrease the  $N^m/N^u$  due to the expansion of the water as its density became lower. This decrease in  $N^m/N^u$  would be a positive reactivity addition, increasing  $k_{eff}$  and further raising power and temperature in a dangerous cycle. If the reactor is under moderated, the same increase in temperature results in the addition of negative reactivity, and the reactor becomes more self-regulating.

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## **Moderator Temperature Coefficient**

The change in reactivity per degree change in temperature is called the *temperature coefficient of reactivity*. Because different materials in the reactor have different reactivity changes with temperature and the various materials are at different temperatures during reactor operation, several different temperature coefficients are used. Usually, the two dominant temperature coefficients are the moderator temperature coefficient and the fuel temperature coefficient.

The change in reactivity per degree change in moderator temperature is called the *moderator temperature coefficient of reactivity*. The magnitude and sign (+ or -) of the moderator temperature coefficient is primarily a function of the moderator-to-fuel ratio. If a reactor is under moderated, it will have a negative moderator temperature coefficient. If a reactor is over moderated, it will have a positive moderator temperature coefficient. A negative moderator temperature coefficient is desirable because of its self-regulating effect. For example, an increase in reactivity causes the reactor to produce more power. This raises the temperature of the core and adds negative reactivity, which slows down, or turns, the power rise.

## **Fuel Temperature Coefficient**

Another temperature coefficient of reactivity, the fuel temperature coefficient, has a greater effect than the moderator temperature coefficient for some reactors. The *fuel temperature coefficient* is the change in reactivity per degree change in fuel temperature. This coefficient is also called the "prompt" temperature coefficient because an increase in reactor power causes an immediate change in fuel temperature. A negative fuel temperature coefficient is generally considered to be even more important than a negative moderator temperature coefficient because fuel temperature immediately increases following an increase in reactor power. The time for heat to be transferred to the moderator is measured in seconds. In the event of a large positive reactivity insertion, the moderator temperature cannot turn the power rise for several seconds, whereas the fuel temperature coefficient starts adding negative reactivity immediately.

Another name applied to the fuel temperature coefficient of reactivity is the fuel doppler reactivity coefficient. This name is applied because in typical low enrichment, light water-moderated, thermal reactors the fuel temperature coefficient of reactivity is negative and is the result of the doppler effect, also called doppler broadening. The phenomenon of the doppler effect is caused by an apparent broadening of the resonances due to thermal motion of nuclei as illustrated in Figure 3. Stationary nuclei absorb only neutrons of energy  $E_0$ . If the nucleus is moving away from the neutron, the velocity (and energy) of the neutron must be greater than  $E_0$  to undergo resonance absorption. Likewise, if the nucleus is moving toward the neutron, the neutron needs less energy than  $E_0$  to be absorbed. Raising the temperature causes the nuclei to vibrate more rapidly within their lattice structures, effectively broadening the energy range of neutrons that may be resonantly absorbed in the fuel. Two nuclides present in large amounts in the fuel of some reactors with large resonant peaks that dominate the doppler effect are uranium-238 and plutonium-240.

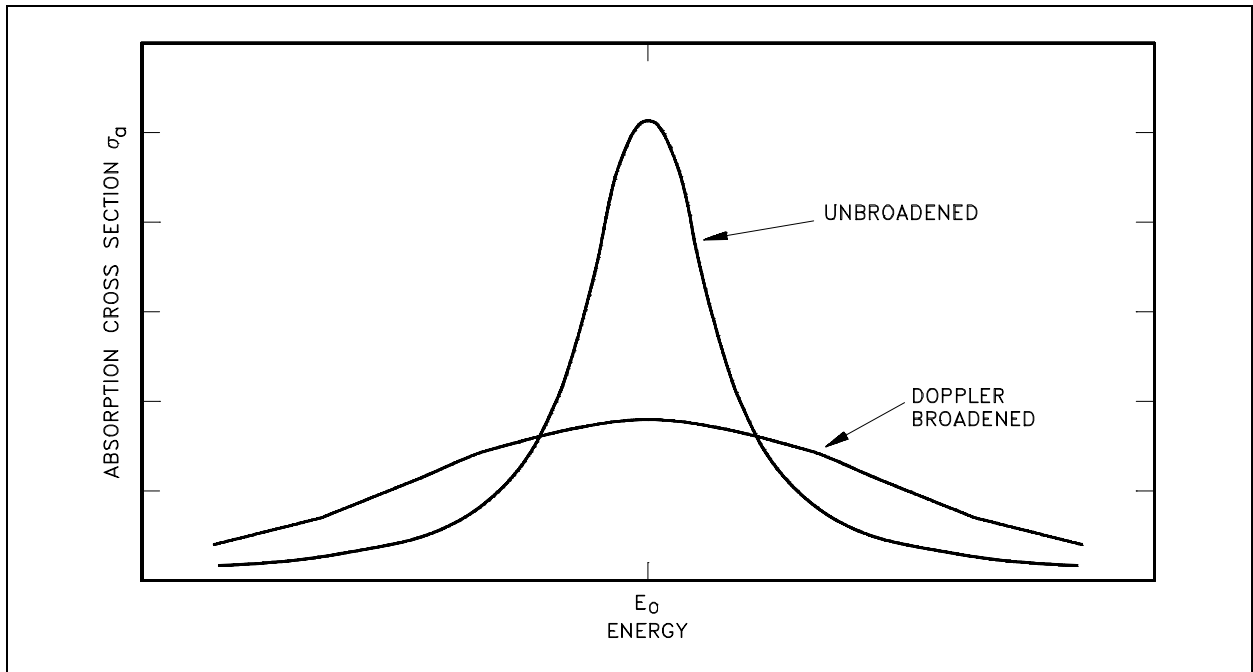


Figure 3 Effect of Fuel Temperature on Resonance Absorption Peaks

### **Pressure Coefficient**

The reactivity in a reactor core can be affected by the system pressure. The *pressure coefficient* of reactivity is defined as the change in reactivity per unit change in pressure. The pressure coefficient of reactivity for the reactor is the result of the effect of pressure on the density of the moderator. For this reason, it is sometimes referred to as the moderator density reactivity coefficient. As pressure increases, density correspondingly increases, which increases the moderator-to-fuel ratio in the core. In the typical under moderated core the increase in the moderator-to-fuel ratio will result in a positive reactivity addition. In reactors that use water as a moderator, the absolute value of the pressure reactivity coefficient is seldom a major factor because it is very small compared to the moderator temperature coefficient of reactivity.

### **Void Coefficient**

In systems with boiling conditions, such as boiling water reactors (BWR), the pressure coefficient becomes an important factor due to the larger density changes that occur when the vapor phase of water undergoes a pressure change. Of prime importance during operation of a BWR, and a factor in some other water-moderated reactors, is the void coefficient. The void coefficient is caused by the formation of steam voids in the moderator. The *void coefficient* of reactivity is defined as the change in reactivity per percent change in void volume. As the reactor power is raised to the point where the steam voids start to form, voids displace moderator from the coolant channels within the core. This displacement reduces the moderator-to-fuel ratio, and in an under moderated core, results in a negative reactivity addition, thereby limiting reactor power rise. The void coefficient is significant in water-moderated reactors that operate at or near saturated conditions.

## **Summary**

The important information in this chapter is summarized below.

### **Reactivity Coefficients Summary**

- The temperature coefficient of reactivity is the change in reactivity per degree change in temperature.
- A reactor is under moderated when a decrease in the moderator-to-fuel ratio decreases  $k_{\text{eff}}$  due to the increased resonance absorption. A reactor is over moderated when an increase in the moderator-to-fuel ratio decreases  $k_{\text{eff}}$  due to the decrease in the thermal utilization factor.
- Reactors are usually designed to operate in an under moderated condition so that the moderator temperature coefficient of reactivity is negative.
- Increasing the moderator temperature will decrease the moderator-to-fuel ratio. Decreasing the moderator temperature will increase the moderator-to-fuel ratio.
- A negative temperature coefficient of reactivity is desirable because it makes the reactor more self-regulating. An increase in power, resulting in an increase in temperature, results in negative reactivity addition due to the temperature coefficient. The negative reactivity addition due to the temperature increase will slow or stop the power increase.
- The fuel temperature coefficient is more effective than the moderator temperature coefficient in terminating a rapid power rise because the fuel temperature immediately increases following a power increase, while the moderator temperature does not increase for several seconds.
- The Doppler broadening of resonance peaks occurs because the nuclei may be moving either toward or away from the neutron at the time of interaction. Therefore, the neutron may actually have either slightly more or slightly less than the resonant energy, but still appear to be at resonant energy relative to the nucleus.
- Uranium-238 and plutonium-240 are two nuclides present in some reactor fuels that have large resonance absorption peaks.

### **Reactivity Coefficients Summary (Cont.)**

- The pressure coefficient of reactivity is the change in reactivity per unit change in pressure.
- The pressure coefficient of reactivity is usually negligible in reactors moderated by subcooled liquids because the density of the liquid does not change significantly within the operating pressure range.
- The void coefficient of reactivity is the change in reactivity per unit change in void volume.
- The void coefficient of reactivity becomes significant in a reactor in which the moderator is at or near saturated conditions.