
CONTROL RODS

Most reactors contain control rods made of neutron absorbing materials that are used to adjust the reactivity of the core. Control rods can be designed and used for coarse control, fine control, or fast shutdowns.

- EO 5.1** **DESCRIBE** the difference between a "grey" neutron absorbing material and a "black" neutron absorbing material.
- EO 5.2** **EXPLAIN** why a "grey" neutron absorbing material may be preferable to a "black" neutron absorbing material for use in control rods.
- EO 5.3** **EXPLAIN** why resonance absorbers are sometimes preferred over thermal absorbers as a control rod material.
- EO 5.4** **DEFINE** the following terms:
- a. **Integral control rod worth**
 - b. **Differential control rod worth**
- EO 5.5** **DESCRIBE** the shape of a typical differential control rod worth curve and explain the reason for the shape.
- EO 5.6** **DESCRIBE** the shape of a typical integral control rod worth curve and explain the reason for the shape.
- EO 5.7** **Given** an integral or differential control rod worth curve, **CALCULATE** the reactivity change due to a control rod movement between two positions.
- EO 5.8** **Given** differential control rod worth data, **PLOT** differential and integral control rod worth curves.
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Selection of Control Rod Materials

Rods of neutron-absorbing material are installed in most reactors to provide precise, adjustable control of reactivity. These rods are able to be moved into or out of the reactor core and typically contain elements such as silver, indium, cadmium, boron, or hafnium.

The material used for the control rods varies depending on reactor design. Generally, the material selected should have a good absorption cross section for neutrons and have a long lifetime as an absorber (not burn out rapidly). The ability of a control rod to absorb neutrons can be adjusted during manufacture. A control rod that is referred to as a "black" absorber absorbs essentially all incident neutrons. A "grey" absorber absorbs only a part of them. While it takes more grey rods than black rods for a given reactivity effect, the grey rods are often preferred because they cause smaller depressions in the neutron flux and power in the vicinity of the rod. This leads to a flatter neutron flux profile and more even power distribution in the core.

If grey rods are desired, the amount of material with a high absorption cross section that is loaded in the rod is limited. Material with a very high absorption cross section may not be desired for use in a control rod, because it will burn out rapidly due to its high absorption cross section. The same amount of reactivity worth can be achieved by manufacturing the control rod from material with a slightly lower cross section and by loading more of the material. This also results in a rod that does not burn out as rapidly.

Another factor in control rod material selection is that materials that resonantly absorb neutrons are often preferred to those that merely have high thermal neutron absorption cross sections. Resonance neutron absorbers absorb neutrons in the epithermal energy range. The path length traveled by the epithermal neutrons in a reactor is greater than the path length traveled by thermal neutrons. Therefore, a resonance absorber absorbs neutrons that have their last collision farther (on the average) from the control rod than a thermal absorber. This has the effect of making the area of influence around a resonance absorber larger than around a thermal absorber and is useful in maintaining a flatter flux profile.

Types of Control Rods

There are several ways to classify the types of control rods. One classification method is by the purpose of the control rods. Three purposes of control rods are listed below.

- Shim rods - used for coarse control and/or to remove reactivity in relatively large amounts.
- Regulating rods - used for fine adjustments and to maintain desired power or temperature.
- Safety rods - provide a means for very fast shutdown in the event of an unsafe condition. Addition of a large amount of negative reactivity by rapidly inserting the safety rods is referred to as a "scram" or "trip."

Not all reactors have different control rods to serve the purposes mentioned above. Depending upon the type of reactor and the controls necessary, it is possible to use dual-purpose or even triple-purpose rods. For example, consider a set of control rods that can insert enough reactivity to be used as shim rods. If the same rods can be operated at slow speeds, they will function as regulating rods. Additionally, these same rods can be designed for rapid insertion, or scram. These rods serve a triple function yet meet other specifications such as precise control, range of control, and efficiency.

Control Rod Effectiveness

The effectiveness of a control rod depends largely upon the value of the ratio of the neutron flux at the location of the rod to the average neutron flux in the reactor. The control rod has maximum effect (inserts the most negative reactivity) if it is placed in the reactor where the flux is maximum. If a reactor has only one control rod, the rod should be placed in the center of the reactor core. The effect of such a rod on the flux is illustrated in Figure 8.

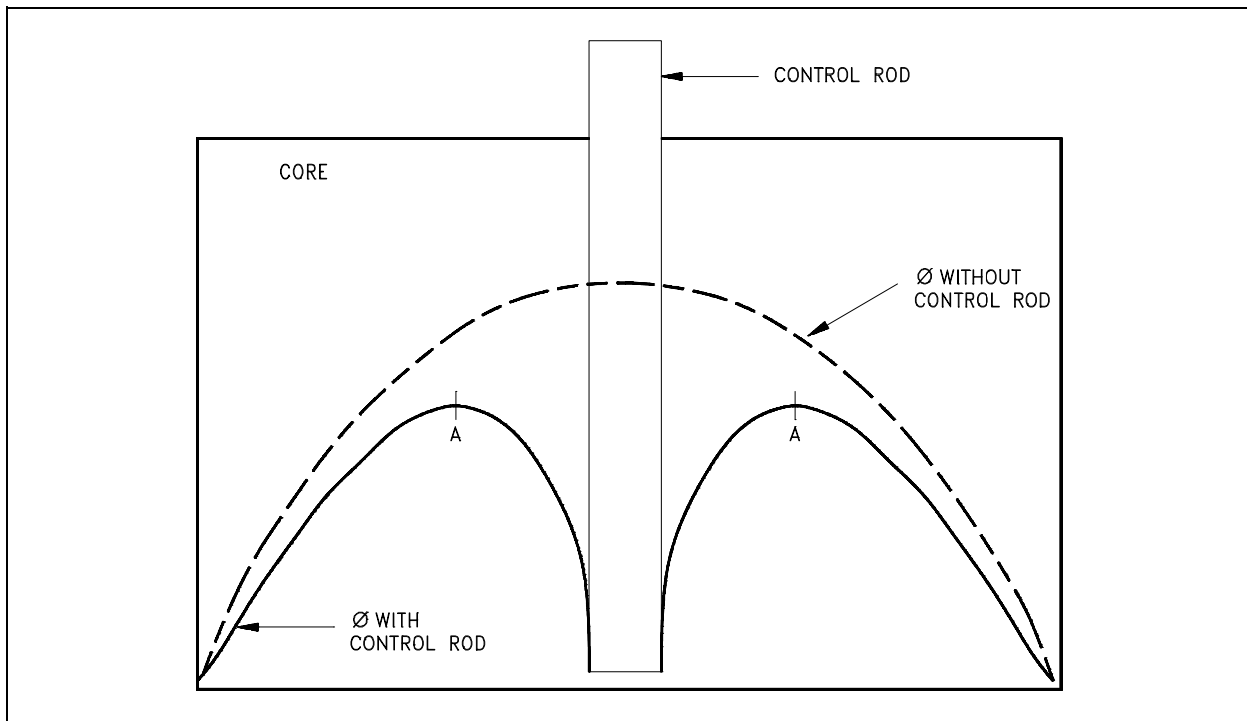


Figure 8 Effect of Control Rod on Radial Flux Distribution

If additional rods are added to this simple reactor, the most effective location is where the flux is maximum, that is, at point A. Numerous control rods are required for a reactor that has a large amount of excess reactivity (that amount of reactivity in excess of that needed to be critical). The exact amount of reactivity that each control rod inserts depends upon the reactor design. The change in reactivity caused by control rod motion is referred to as control rod worth.

Integral and Differential Control Rod Worth

The exact effect of control rods on reactivity can be determined experimentally. For example, a control rod can be withdrawn in small increments, such as 0.5 inch, and the change in reactivity can be determined following each increment of withdrawal. By plotting the resulting reactivity versus the rod position, a graph similar to Figure 9 is obtained. The graph depicts integral control rod worth over the full range of withdrawal. The *integral control rod worth* is the total reactivity worth of the rod at that particular degree of withdrawal and is usually defined to be the greatest when the rod is fully withdrawn.

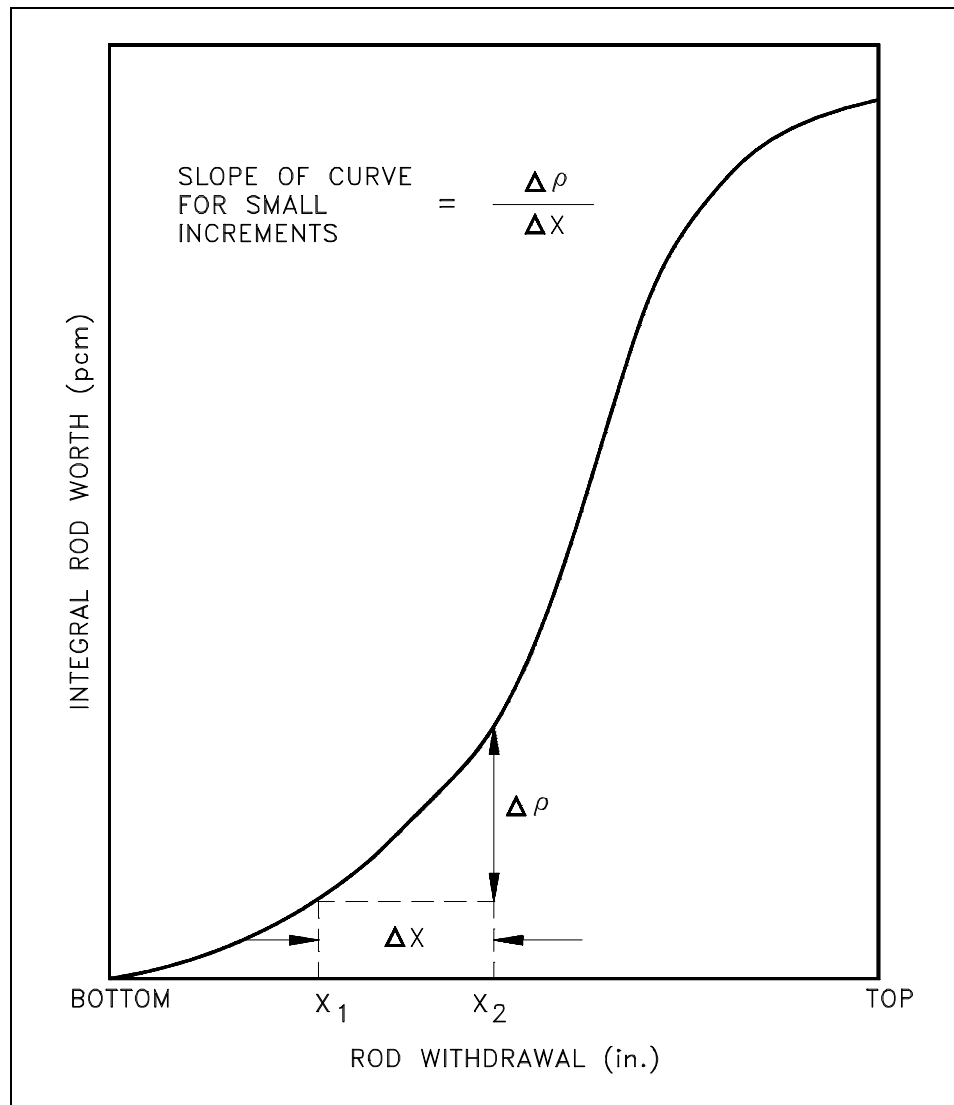


Figure 9 Integral Control Rod Worth

The slope of the curve ($\Delta\rho/\Delta x$), and therefore the amount of reactivity inserted per unit of withdrawal, is greatest when the control rod is midway out of the core. This occurs because the area of greatest neutron flux is near the center of the core; therefore, the amount of change in neutron absorption is greatest in this area. If the slope of the curve for integral rod worth in Figure 9 is taken, the result is a value for rate of change of control rod worth as a function of control rod position. A plot of the slope of the integral rod worth curve, also called the differential control rod worth, is shown in Figure 10. At the bottom of the core, where there are few neutrons, rod movement has little effect so the change in rod worth per inch varies little. As the rod approaches the center of the core its effect becomes greater, and the change in rod worth per inch is greater. At the center of the core the differential rod worth is greatest and varies little with rod motion. From the center of the core to the top, the rod worth per inch is basically the inverse of the rod worth per inch from the center to the bottom.

Differential control rod worth is the reactivity change per unit movement of a rod and is normally expressed as ρ/inch , $\Delta k/k$ per inch, or pcm/inch. The integral rod worth at a given withdrawal is merely the summation of all the differential rod worths up to that point of withdrawal. It is also the area under the differential rod worth curve at any given withdrawal position.

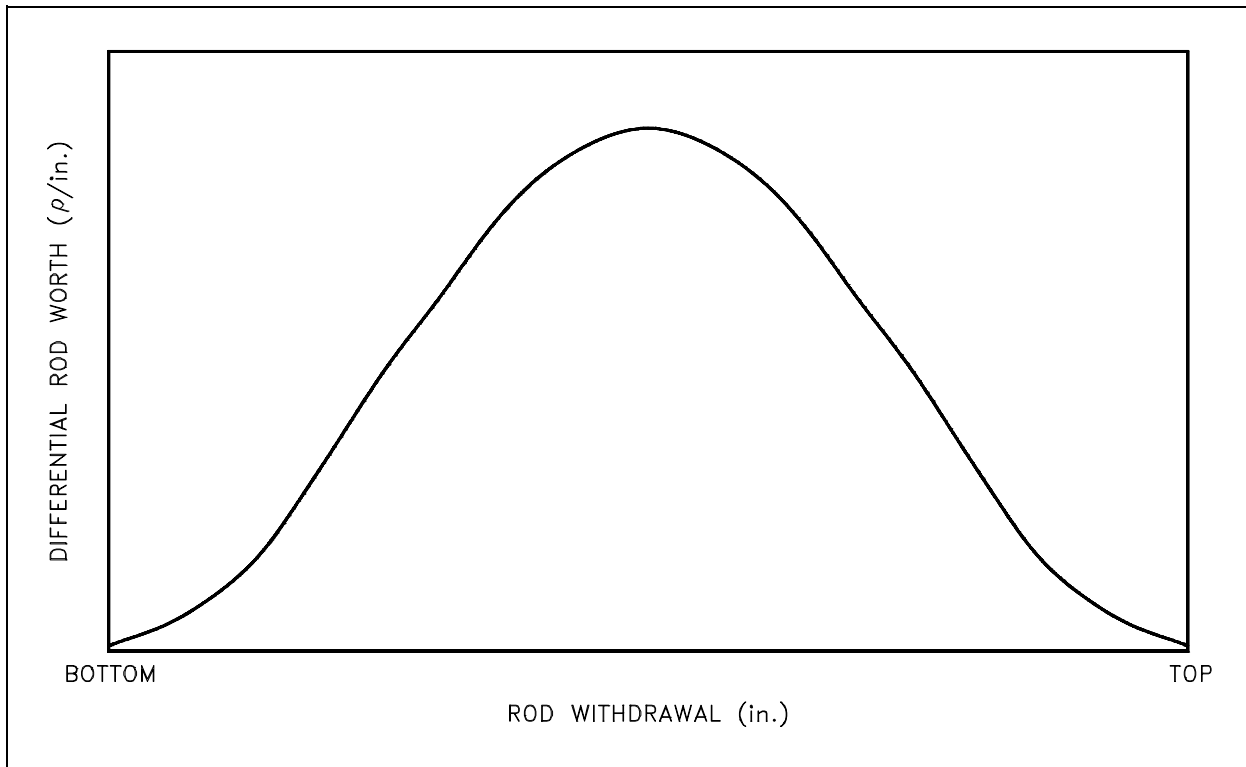


Figure 10 Differential Control Rod Worth

The following exercises are intended to reinforce an understanding of the concepts of integral and differential rod worth.

Example 1:

Using the integral rod worth curve provided in Figure 11, find the reactivity inserted by moving the rod from 12 inches withdrawn out to 18 inches withdrawn.

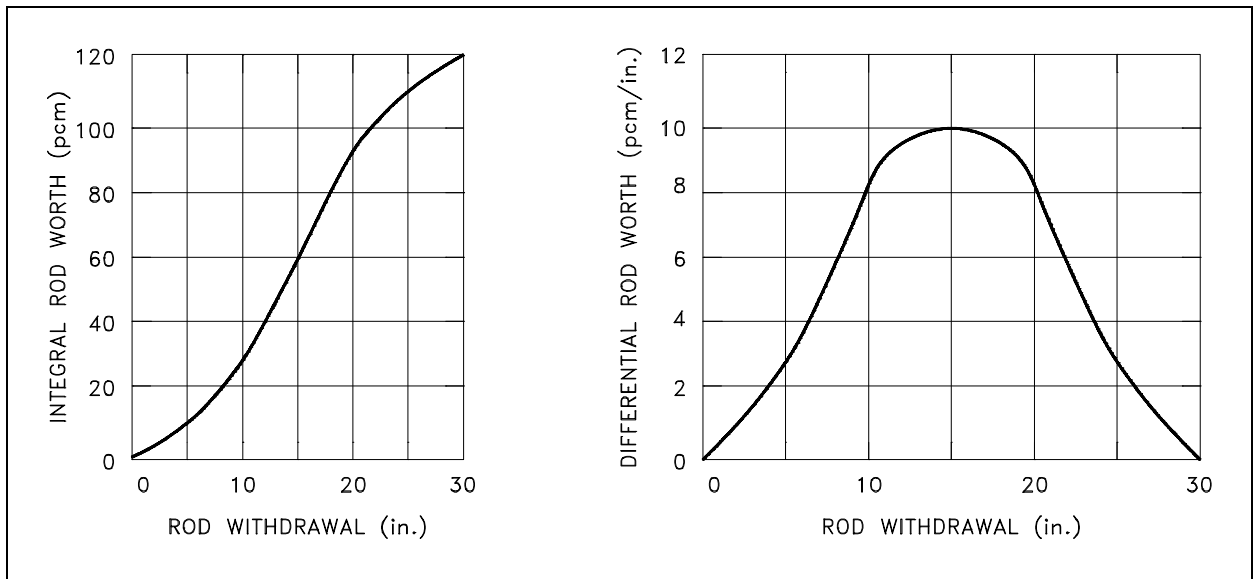


Figure 11 Rod Worth Curves for Example Problems

Solution:

The integral rod worth at 12 inches is 40 pcm and the integral rod worth at 18 inches is 80 pcm.

$$\begin{aligned}\Delta\rho &= \rho_{\text{final}} - \rho_{\text{initial}} \\ &= \rho_{18} - \rho_{12} \\ &= 80 \text{ pcm} - 40 \text{ pcm} \\ &= 40 \text{ pcm}\end{aligned}$$

Example 2:

Using the differential rod worth curve provided in Figure 11, calculate the reactivity inserted by moving the rod from 10 inches withdrawn to 6 inches withdrawn.

Solution:

The solution is basically given by the area under the curve for the interval. The answers obtained in the following approximation may vary slightly depending upon the degree of approximation.

Method 1. Treating the range from 10 inches to 6 inches as a trapezoid, that is, taking the end values of pcm/inch and multiplying their average by the 4 inches moved yields the following.

$$\left(\frac{8 \frac{\text{pcm}}{\text{inch}} + 3 \frac{\text{pcm}}{\text{inch}}}{2} \right) (4 \text{ inches}) = -22 \text{ pcm}$$

This is negative because the rod was inserted.

Method 2. Using the central value of rod position at 8 inches yields an average rod worth of 5.5 pcm/inch. Multiplying by the 4 inches of rod travel yields the answer.

$$(5.5 \text{ pcm/in.})(4 \text{ in.}) = -22 \text{ pcm}$$

Method 3. Breaking the rod travel total into two parts (10 inches to 8 inches and 8 inches to 6 inches) yields:

$$\left(\frac{8 \frac{\text{pcm}}{\text{inch}} + 5.5 \frac{\text{pcm}}{\text{inch}}}{2} \right) (-2 \text{ inches}) = -13.5 \text{ pcm}$$

$$\left(\frac{5.5 \frac{\text{pcm}}{\text{inch}} + 3 \frac{\text{pcm}}{\text{inch}}}{2} \right) (-2 \text{ inches}) = -8.5 \text{ pcm}$$

$$(-13.5 \text{ pcm}) + (-8.5 \text{ pcm}) = -22 \text{ pcm}$$

In this example the various approximations used did not cause any difference because the problem deals with a section of the curve with an approximately constant slope. To obtain the value over the interval between 8 inches and 20 inches, however, would require the use of several subintervals (as in the last approximation) to obtain an accurate answer.

Example 3:

For the differential rod worth data given below, construct differential and integral rod worth curves.

<u>Interval (inches)</u>	<u>Reactivity Inserted (pcm)</u>
0 to 2	10
2 to 4	20
4 to 6	40
6 to 8	60
8 to 10	60
10 to 12	40
12 to 14	20
14 to 16	10

Solution:

Differential rod worth:

For each interval, the number of pcm/inch must be determined. For example, in the first interval (0 inches to 2 inches), 10 pcm is added. Therefore, the differential rod worth equals an average 5 pcm/inch. This value of differential rod worth is plotted at the center of each interval. The center of the interval 0 inches to 2 inches is 1 inch. The values of pcm/inch for each interval are then listed as shown below and plotted on Figure 12.

<u>Interval Center</u>	<u>pcm/inch</u>
1	5
3	10
5	20
7	30
9	30
11	20
13	10
15	5

Integral rod worth:

To plot the integral rod worth, merely develop a cumulative total of the reactivity added after each interval and plot the summed reactivity insertion vs. rod position as shown in Figure 12.

<u>Interval Endpoint</u>	<u>Summed Reactivity</u>
2	10
4	30
6	70
8	130
10	190
12	230
14	250
16	260

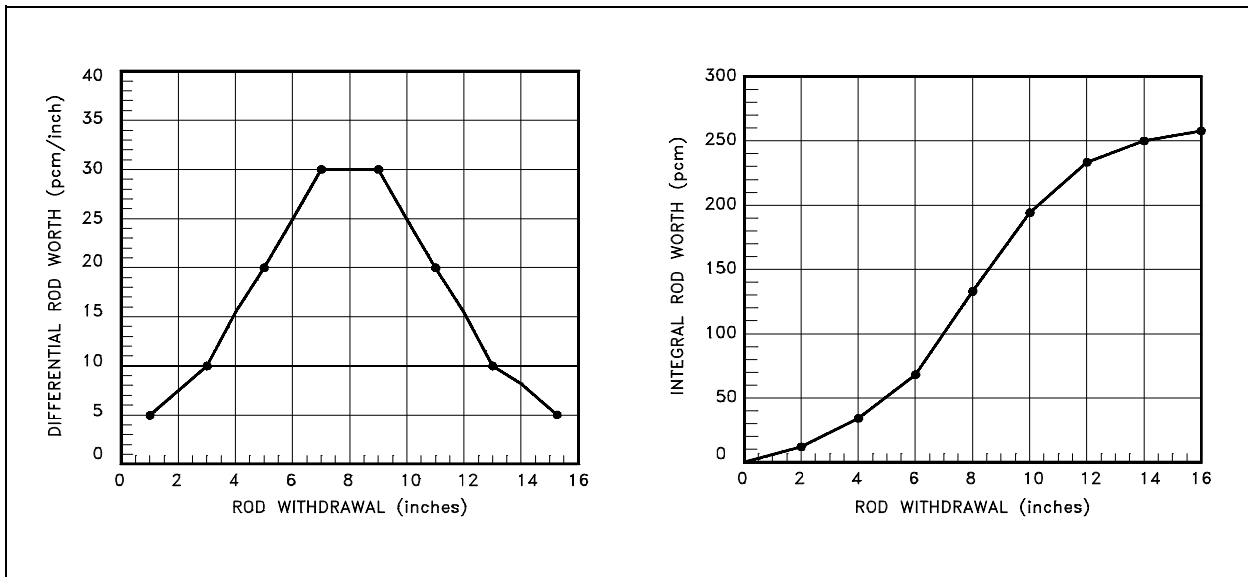


Figure 12 Rod Worth Curves From Example 3

If an integral rod worth curve is supplied, a differential rod worth curve can be generated from the integral rod worth data. Merely select a convenient interval of rod withdrawal, such as 1 inch or 2 inches. Then, determine from the curve the amount of reactivity added for each constant interval of rod withdrawal. A plot of this reactivity addition versus rod withdrawal represents differential rod worth.

Rod Control Mechanisms

The control rod insertion rates on a scram are designed to be sufficient to protect the reactor against damage in all transients that are expected to occur during the life of the reactor.

During normal rod motion, the control rods must be able to move rapidly enough to compensate for the most rapid rate at which positive reactivity is expected to build within the reactor in order to provide positive control. The transient that is normally considered when setting this minimum rod speed is the burnout of maximum peak xenon while at full power. Xenon burnout is usually the most rapid, non-accident transient expected. The maximum rod speed is normally limited in order to reduce the severity of an accident involving the continuous withdrawal of control rods.

Summary

The important information in this chapter is summarized on the following page.

Control Rods Summary

- A black neutron-absorbing material absorbs essentially all incident neutrons. A grey neutron-absorbing material absorbs only part of the incident neutrons.
- A grey neutron-absorbing material may be preferable to a black neutron-absorbing material in the construction of control rods because the grey absorber causes smaller depressions in neutron flux and power in the vicinity of the rod.
- Resonance absorbers are sometimes preferred to thermal absorbers as control rod materials because they have a larger area of influence and result in a flatter flux profile.
- Integral control rod worth is the total reactivity worth of the control rod at a particular degree of withdrawal from the core.
- Differential control rod worth is the reactivity change per unit movement of a control rod.
- The typical differential control rod worth curve has a bell shape. It has very low values at the top and bottom of the core and a maximum value at the center of the core. The curve has this shape because rod worth is related to neutron flux, and flux is highest in the center of the core.
- The typical integral control rod worth curve has an "S" shape. It has a relatively flat slope at the top and bottom of the core and a maximum slope at the center of the core.
- Integral or differential control rod worth curves can be used to determine the reactivity change due to a control rod movement between two positions.
- Integral or differential control rod worth curves can be plotted based on measured control rod worth data.