Module 13

Reactivity Control

13.1 MODULE OVERVIEW

Reactivity regulation

Reactivity control mechanisms are needed for ***reactor regulation*** and for ***reactor protection***. The principal objectives of this module are to analyze the requirements for ***reactivity regulation*** arising from changes in the operating conditions of the reactor, and to discuss how these requirements can most efficiently be met. We start by using the knowledge accumulated by study of earlier modules to summarize the reactivity changes expected over the operational life of the reactor. We then discuss possible ways to vary reactivity in terms of the six-factor formula and describe in detail the methods of reactivity control actually used, noting the advantages and disadvantages of each. Finally, we look at the requirements for ***shutdown systems***, comparing the reactivity depth and response time of the three mechanisms used in CANDU reactors—moderator dump, shut-off rods and poison injection.

Shutdown systems

13.2 MODULE OBJECTIVES

After studying this module, you should be able to:

i) Distinguish between the requirements for reactor regulation and reactor protection.

ii) List the principal sources of reactivity variation which arise during reactor operation.

iii) Identify the terms in the six-factor formula which might be most conveniently varied to compensate for the above changes.

iv) List some advantages and disadvantages of the various methods used for automatic reactor regulation, long-term reactivity control and fuel burnup.

v) List the advantages and disadvantages of moderator dump, shut-off rods and poison injection for reactor shutdown.

13.3 REACTIVITY MECHANISMS

13.3.1 Reactor Regulation And Protection

r regulation and protection

Reactivity mechanisms represent the final control elements which cause changes in the neutron multiplication constant k (or reactivity Δk) and therefore in reactor power. There are two separate requirements of reactivity mechanisms which are fulfilled by independent systems. These requirements are:

a) ***Reactor regulation***

The four basic functions of the reactor regulation systems are:

i) Maintain $k = 1$ for steady power operation.

ii) Provide small changes (+ve or – ve) in k to change reactor power.

iii) Prevent the development of flux oscillations.

iv) Provide power setback and stepback in the event that certain operating parameters are outside the normal regulating range of values.

b) ***Reactor protection***

The principal purpose of the protective system is to insert a large amount of negative reactivity for rapid shutdown of the reactor ***(trip)*** in the event that one or more operating parameters are outside the acceptable range of values.

The use of separate systems for reactor regulation and safety is a cornerstone of the safety philosophy of CANDU reactors. In fact, from a practical viewpoint no single system can adequately fulfill all requirements for reactor regulation, let alone regulation and protection together.

13.3.2 Requirements For Reactivity Mechanisms For Reactor Regulation

The complex physical and nuclear changes occurring in the core during reactor operation mean that an effective regulating system will have to consist of more than one type of reactivity mechanism. A convenient breakdown of the various in-core reactivity changes which require compensating and regulating controls is listed in Table 13.1 and grouped in terms of the two most important parameters of any reactivity mechanism, namely:

i) ***reactivity worth*** (or depth) Δk (mk) which must be somewhat larger than the reactivity change for which the mechanism must compensate or control, and

ii) ***operational time interval***, or the time during which the mechanism must be able to supply or remove reactivity, which will determine the reactivity insertion rate (sometimes called the ramp reactivity rate), Δk per unit time (mk/s).

Each tabulated reactivity change is briefly described below and the typical worths necessary to control these changes as they occur in CANDU stations are shown for comparison in Table 13.2. Where these values change from fresh fuel to equilibrium fuel conditions, the difference is noted.

ımmary of operational reactivity anges

TABLE 13.1

In-core reactivity changes

	Source of in-core reactivity changes	**Depth (Δk)**	**Time interval**
a)	Power changes, hot shutdown to hot full power	medium (- ve)	minutes
b)	Fuel and coolant temperature changes	medium (+ve,-ve)	seconds, minutes
c)	Moderator temperature change	medium (+ve,-ve)	minutes
d)	Fresh fuel burn up	large (-ve)	6 - 7 months
e)	Equilibrium xenon load build up	large (-ve)	40 hours
f)	Xenon transient build up	large (-ve)	<12 hours
g)	Flux oscillations	medium (+ve,-ve)	15 - 30 hours
h)	Equilibrium fuel burn up	small (-ve)	days (continuous)
i)	Plutonium and samarium build up	medium (+ve)	300 hours

13.4 IN-CORE REACTIVITY CHANGES

a) Power changes (See Module 12)

Power changes

Reactivity changes as the temperatures of the fuel and coolant increase when power increases from a hot shutdown condition to a hot full-power condition. Under normal (that is, non-excursion) conditions, there will be a negative reactivity change called the ***power coefficient of reactivity*** (see Figure 12.10). This is tabulated in Table 13.2. In order to maintain criticality, an equal but opposite reactivity worth must be supplied by some other means (for example, by removing an equivalent reactivity worth from the zone control system).

b) Fuel and coolant temperature change (see Module 12)

Temperature changes

As the fuel and coolant are heated from a cold shutdown condition (about 25°C) to a hot shutdown condition (about 290°C), reactivity decreases substantially for the fresh core but increases somewhat for the equilibrium core (Figure 12.10).

c) Moderator temperature changes (See Module 12)

Normally, moderator temperature is kept fairly constant (typically 70°C maximum in the calandria and 40°C at the heat exchanger outlets) but variation can be obtained by changing the rate of heat removal from the heat exchangers. The sign of the accompanying coefficient depends on poison content for a freshly-fuelled core, but it is always positive for an equilibrium core.

esh fuel burnup

d) **Fresh fuel burnup** (See Module 7)

As the fuel burns up from the fresh to the equilibrium condition over a period of about six months, there is a large increase in negative reactivity load due to the build up of Pu-240 and long-lived neutron absorbing fission products (not including Xe-135), and to depletion of fissile material (Figure 7.7). This is a slow but continuous reactivity change.

non

e) **Equilibrium xenon load build up** (See Module 11)

Following start-up after a long reactor shutdown (>2-3 days), an equilibrium reactivity load (up to -28 mk) will be built up due to an accumulation of Xe-135 in the fuel.

f) **Xenon transient buildup** (See Module 11)

Within 12 hours of a reactor shutdown (or large derating due to load-following or operational problems), there is a very large transient rise in Xe-135 poison concentration (up to – 80 mk above the equilibrium level at Pickering). To enable us to restart the unit, xenon override capability is provided to compensate for this negative reactivity. The reactor can be restarted if the override reactivity can be inserted within a time period after shutdown known as the ***override time***. Actual reactivities available and the override time thus obtained are listed in Table 13.2.

oscillations

g) **Flux oscillations** (See Module 11)

Localized flux or power changes in the core (from, for example, refuelling part of a channel or movement of a control rod), can initiate quite large undamped power swings (xenon oscillations) with periods between 15 and 30 hours.

The *zone control system* is used to counter these unbalanced reactivity loads in various regions of the core. Total reactivity worths of these systems are shown in Table 13.2. The zone control systems are also used for bulk power control.

h) **Equilibrium fuel burnup** (See Module 7)

Equilibrium fuel burnup

At equilibrium fuel burnup, when the operating target excess reactivity is reached, fission products continue to build up and fissile material continues to be depleted. Continuous on-power refuelling is, of course, the most important method of compensating for this continual depletion of fissile material at equilibrium burnup. The rate of reactivity loss for CANDU reactors without refuelling is shown in Table 13.2 and, for comparison, the reactivity increases due to the refuelling of a single typical central channel are also listed.

i) **Plutonium and samarium buildup** (See Modules 7 and 11)

Pu and Sm buildup

After shutdown, plutonium builds up from the decay of neptunium, adding positive reactivity, and samarium builds up from the decay of promethium, adding negative reactivity. The overall effect is positive, as shown in Table 13.2.

As you can see, the range of reactivity depths and insertion rates makes it impractical to try to design a single control mechanism.

Table 13.2
Comparison Of Station Reactivity Loads

	Reactivity Worth Change		Pickering A & B	Bruce A & B	Lepreau	Darlington	Gentilly-2
a)	Power coefficient (hot shutdown-hot full power)	fresh fuel	-7 mk	-9 mk	-6.1 mk	-9 mk	-9 mk
		equilibrium fuel	-3 mk	-3.5 mk	-3 mk	-3 mk	-3 mk
b)	Fuel and coolant (temperature 25°C to 275 °C)	fresh fuel	-8 mk	-9 mk	-6 mk	-7 mk	-1.5 mk
		equilibrium fuel	+2.5 mk	+3 mk	+3 mk	+2.5 mk	+8 mk
c)	Moderator temperature coefficient	fresh fuel (Note 1)	-0.06 mk/°C	-0.07 mk/°C	+0.045 mk/°C	-0.097 mk/°C	+0.045 mk/°C
		equilibrium fuel	+0.08 mk/°C	+0.09 mk/°C	+0.097 mk/°C	+0.057 mk/°C	+0.097 mk/°C
d)	Fresh fuel burnup		-25 mk	-22 mk	-20 mk	-22 mk	-20 mk
e)	Xe Equilibrium load		-28 mk	-28 mk	-28 mk	-28 mk	-28 mk
f)	Xe Peak load		-98 mk	-133 mk	-136 mk	-143 mk	-136 mk
	Xe Override capability Note 2)		+18 mk	+15 mk	+15 mk	+18 mk	+15 mk
	Xe Override time		45 min.	40 min.	30 min.	30 min.	30 min.
g)	Zone control reactivity worth		5.4 mk	6 mk	7.1 mk	7 mk	7.1 mk
h)	Reactivity loss (equilibrium fuel)		-0.3 mk/day	-0.5 mk/day	-0.41 mk/day	-0.41 mk/day	-0.41 mk/day
	Reactivity gain per refuelled central channel		+0.2 mk	+0.2 mk	+0.2 mk	+0.1 mk	+0.2 mk
i)	Plutonium and samarium buildup		+6 mk	+6 mk	+6 mk	+6 mk	+6 mk

NOTES: 1) Will depend on poison content; Lepreau and G-2 values are with 8.5 mg/kg boron in moderator.
2) New elements only; will decrease by 30% at end-of-life burnup.

13.5 METHODS OF REACTIVITY CONTROL

Before we can discuss reactivity mechanisms, we must look at the theoretical methods of reactivity control. Recalling that

Reactivity control and the six-facto formula

$$k = \varepsilon p \eta f \Lambda_f \Lambda_t$$

we will examine which of the six factors we can use to change or control reactivity.

First, the ***fast fission factor*** (ε) and the ***resonance escape probability*** (p) cannot be easily varied. They depend on the amount of U-238 present and the lattice spacing in the reactor. Therefore we will make no attempt to control reactivity by controlling ε or p.

Next is the ***reproduction factor*** (η). From equation (5.4)

$$\eta = \nu \frac{\Sigma_f(\text{fuel})}{\Sigma_a(\text{fuel})}$$

If we increase the amount of fissile material present, we will increase η. That is, more neutrons will be produced per neutron absorbed by the fuel.

Thermal utilization (f) is the fraction of thermal neutrons absorbed by the fuel to those absorbed in the whole core. From equation 5.5

$$f = \frac{\Sigma_a(\text{fuel})\ \phi\ (\text{fuel})}{\Sigma_a(\text{total reactor})\ \phi\ (\text{total reactor})}$$

If we increase or decrease the amount of non-fuel absorption, we vary f and hence the reactivity. Variation of neutron absorption is by far the most common method of control.

Finally, we have the fast and thermal non-leakage probabilities (Λ_f, Λ_t). If we vary the leakage of neutrons from the reactor, we will vary reactivity.

13.6 REACTIVITY MECHANISMS

In order to discuss the reactivity mechanisms currently in use, we shall divide them into five groups based on their basic function in the reactor. The five functional groups are:

activity mechanisms

i) Automatic reactor regulation — (includes bulk power and zone control).

ii) Xenon override.

iii) Long-term reactivity control - (includes fresh fuel burnup, the buildup of equilibrium xenon and the buildup of plutonium and samarium after shutdown).

iv) Equilibrium fuel burnup.

v) Shutdown systems.

For each category, we will discuss the methods used and the significant advantages and disadvantages of those methods. Table 13.3 indicates the systems used at each station and the reactivity depth of each system.

Table 13.3

Reactivity Control Systems For CANDU Reactors

		Pickering A	Bruce A	Pickering B	Bruce B	Point Lepreau	Darlington	Gentilly-2
Reactor Regulation (Note 1)	Primary	14 Liquid Control Zones (5.4 mk)	14 Liquid Control Zones (6 mk)	14 Liquid Control Zones (6 mk)	14 Liquid Control Zones (6 mk)	14 Liquid Control Zones (7 mk)	14 Liquid Control Zones (7 mk)	14 Liquid Control Zones (7 mk)
	Secondary		4 Control Absorbers (7 mk)	4 Control Absorbers (10 mk)	4 Control Absorbers (9.5 mk)	4 Control Absorbers (10.8 mk)	4 Control Absorbers (8 mk)	4 Control Absorbers (10.3 mk)
Xenon Override		18 Adjuster Rods (10 mk)	- -	21 Adjuster Rods (18 mk)	15 Adjuster Rods (18 mk)	21 Adjuster Rods (15 mk)	24 Adjuster Rods (16 mk)	21 Adjuster Rods (15 mk)
Long-term Reactivity Control		Moderator Poison Addition (Variable reactivity depending on poison concentration)						
Equilibrium Fuel Burnup		All stations use on-power refuelling						
Shutdown Systems	SDS 1	11 Shutoff Rods (24 mk)	30 Shutoff Rods (40 mk)	28 Shutoff Rods (48 mk)	32 Shutoff Rods (69 mk)	28 Shutoff Rods (82 mk)	32 Shutoff Rods (66 mk)	28 Shutoff Rods (83.5 mk)
	SDS 2	Moderator Dump (Note 2)	Poison Injection (55 mk in 2.9 s)	Poison Injection (N/A)	Poison Injection (55 mk in 2.9 s)	Poison Injection (95 mk in 3 s)	Poison Injection (59 mk in 5 s)	Poison Injection (46 mk in 0.75 s)

NOTES: (1) The primary system is normally used for reactor regulation. If the primary system is unavailable or has insufficient reactivity depth, the secondary system will act automatically.

(2) Operation of the dump system at Pickering A is not entirely independent of the shutoff rods.

13.6.1 Automatic Reactor Regulation

tomatic regulation

The following methods may be used (the first is included for completeness only, as it is no longer used in practice):

a) *Moderator level control*

Small changes in moderator level alter the thickness of the reflector on top of the reactor, thus varying leakage.

Advantages

i) Easily added to systems using moderator dump as a backup emergency shutdown mechanism.

Disadvantages

i) Zone control is not possible.

ii) Lowering the moderator level distorts the overall flux distribution.

b) *Control absorbers*

Solid rods, composed of cadmium in stainless steel, which can be operated vertically in the core. Because they are parasitic absorbers, the control absorbers change the thermal utilization.

Advantages

i) Provide additional negative reactivity at minimal cost.

Disadvantages

i) In-core guide tubes represent permanent reactivity loss (fuel burnup loss).

c) Liquid zone control (LZC)

Zone control compartments inside the reactor which contain a variable amount of light water (a mild neutron absorber). Varying the amount of light water in the LZC system varies parasitic absorption and hence the thermal utilization.

Advantages

i) Individual zone levels can be independently varied for zone control.

ii) Operating equipment is mainly outside containment and therefore accessible (with due regard to radiation levels) during reactor operation.

iii) Cooling is easily accomplished.

iv) There is only slight distortion of the overall flux pattern.

Disadvantages

i) Requires special design to ensure that the zones fail safe (that is, fill).

ii) In-core structure represents a reactivity (or fuel burnup) loss.

anon override

13.6.2 Xenon Override

Adjuster rods, whose primary purpose is to provide flux flattening, can also be used as a positive reactivity shim or for xenon override. These are rods of a neutron-absorbing material (cobalt or stainless steel). They are normally fully inserted in the reactor thus increasing parasitic absorption (decreasing f). Positive reactivity is provided by withdrawing the adjuster rods.

Advantages

i) Adjuster rods serve the dual function of providing flux flattening (radial and axial) as well as xenon override.

ii) There is no significant decrease in reactivity worth over normal lifetime.

Disadvantages

i) Presence of adjusters results in a fuel burnup penalty of about 8%. (The adjusters reduce f and so we must increase one of the other factors. Thus η is increased by reducing the attainable burnup.)

ii) Withdrawal of adjusters causes local flux peaking and may impose restraints on power output.

13.6.3 Long-term Reactivity Control

Long-term reactivity control

The method of long-term reactivity control currently in use is the addition of soluble poison to the moderator. While solid rods could be used for this purpose, soluble poison systems are cheaper and cause no flux distortions. However, adding poison to the moderator reduces the flux reaching the ion chambers sufficiently that the power reading from out-of-core ion chambers must be corrected for the presence of the poison.

Poisons

The poisons used are ***boron*** (in the form of boric acid) and ***gadolinium*** (in the form of gadolinium nitrate). Boron and gadolinium in their natural forms have two and seven isotopes respectively. Most of the isotopes have relatively small absorption cross-sections for thermal neutrons, but boron has one strongly-absorbing isotope (B-10) and gadolinium two (Gd-155 and Gd-157). The relevant data are given in Table 13.4.

Table 13.4

Strongly-absorbing isotopes of boron and gadolinium

Isotope	Natural abundance (%)	Thermal absorption cross-section (b)
B-10	19.9	3840
Gd-155	14.8	6.1×10^4
Gd-157	15.65	2.55×10^5

The liquid poisons are added to the moderator in a controlled manner and are removed either by burnup in the neutron flux or by ion exchange. The burnup rate of each poison is proportional to its cross-section. Since the cross-section of boron is lower than that of gadolinium, it is more suitable for dealing with longer-term reactivity variations, like those associated with fresh fuel burnup. Gadolinium, on the other hand, is used as compensation for medium-term reactivity variations, such as xenon transients. The situations for which each poison is used are summarized in Table 13.5.

Boron has the disadvantage that its removal by ion exchange is much slower than that of gadolinium, and much more expensive because it uses significantly more ion exchange resin. A disadvantage of gadolinium is that it interferes with the aqueous recombination of the D_2 and O_2 produced by radiolysis of the D_2O, which leads to a build up of these in the cover gas.

pplications of boron and adolinium

Table 13.5 Specific applications of moderator poisons

APPLICATION	POISON & WHY CHOSEN	WHY POISON ADDED
Fresh fuel burnup simulation prior to initial startup and during initial operation when the unit contains fresh fuel.	Boron - slow boron burnup rate in neutron flux and slow IX boron removal rate closely match slow fuel burnup rate and slow fuel fission product buildup.	To compensate for extra reactivity of fresh fuel, due to absence of longer lived fission product poisons and to compensate for the plutonium peak in fresh fuel.
During fuelling	Boron - burnup rate and removal rate of boron more closely match reactivity changes of new fuel.	To compensate for the extra reactivity of new fresh bundles, in part due to absence of longer lived fission product poisons.
During overfuelling (fuelling machine reactivity shim control).	Boron - again burnup rate and removal rate of boron more closely match reactivity changes of new fuel.	To compensate for extra reactivity of the excess fuel.
During an extended outage (guaranteed shutdown).	Gadolinium - IX removal rate is faster. Gadolinium is more soluble than boron and has a higher negative mk worth per ppm dissolved.	To make the reactor deeply subcritical. To compensate for loss of xenon and other reactivity effects.

Following startup after a poison outage (xenon transient).	<u>Gadolinium -</u> xenon will build up at almost the same rate as gadolinium is burned out in neutron flux. The slight mismatch can be compensated by adding Gd from Gd tank or removing Gd with IX column.	To compensate for lack of xenon after the poison outage.
After a large increase in power following sustained operation at a lower power level.	<u>Gadolinium -</u> will burn out at almost the same rate as xenon builds up.	Large increase in power after sustained low power operation will initially decrease the xenon level, due to increased neutron flux. The poison, if required, will compensate for the loss of xenon. Xenon will, over time, increase to a new higher equilibrium concentration.

The concentration of boron or gadolinium in the moderator can be measured by chemical sampling. Once the poison has been exposed to irradiation at power, however, its reactivity worth is no longer proportional to its concentration, due to the depletion of the higher cross-section isotopes, which burn up more rapidly than the others. The situation for boron and gadolinium differs, as explained below.

<u>Boron</u>: The process by which boron-10 is removed is the B-10(n,α)Li-7 transmutation reaction. Chemical sampling will measure only the remaining boron concentration, without indicating the proportion of boron-10 remaining. Consequently, the total reactivity worth is uncertain, since we cannot be sure how much of the reduction in boron concentration is due to burnup and how much to purification by the ion exchange columns.

Gadolinium: This situation is different, because neutron absorption by Gd-155 and Gd-157 simply leads to Gd-156 and Gd-158. Consequently, the overall gadolinium concentration does not change with irradiation. The reactivity worth, however, will still decrease owing to the preferential burnup of the high absorption isotopes. Again, the total reactivity worth of the poison will be uncertain, since we cannot be sure how much Gd-155 and Gd-157 have been burnt up.

13.6.4 Equilibrium Fuel Burnup

quilibrium fuel burnup

On-power refuelling is used in all large CANDUs. This keeps the amount of fissile material approximately constant by replacing irradiated fuel with fresh fuel more or less continuously. This system has several distinct advantages over batch refuelling:

i) No downtime for refuelling

ii) Better average fuel burnup

iii) Better flux shaping

iv) Failed fuel can be removed easily without a shutdown.

v) It avoids the very large poison shim that is required if batch refuelling is used.

There are some disadvantages, mainly the high capital cost of the refuelling machines and their high maintenance costs.

If the refuelling machines are unavailable for some reason, the reactor can continue to operate for only a limited time. The CANDU 600, for example, consumes about 0.4 mk per day (that is, the reactivity worth of the fuel diminishes at that rate). If the LZC were at 50% at full power in an equilibrium condition, about 2 mk of excess reactivity would be available. This would give approximately five days of running before shim operation by removal of a bank of adjusters would be necessary. With adjusters out of core, a small power reduction (derating) may be required because of the loss of flux flattening.

13.6.5 Shutdown Systems

Shutdown systems

Early CANDU designs had a single shutdown system. As the design of the reactor became more sophisticated, the requirement for extremely high reliability dictated that two independent shutdown systems be provided. There are presently three types of shutdown systems available.

a) Shutoff rods

Shutoff rods

These are hollow cylinders of neutron-absorbing material (normally cadmium sheathed in stainless steel) which can be dropped into the reactor under gravity. Their presence greatly increases parasitic absorption which reduces thermal utilization.

Advantages

i) Rapid reactivity insertion as required for protection in certain worst-case accidents. Figure 13.1(a) shows reactivity versus time for CANDU 600 shutoff rods. Note that the rods have inserted more than –60 mk in 2 seconds.

ii) Rapid recovery from a trip is possible (about 3 minutes to withdraw rods).

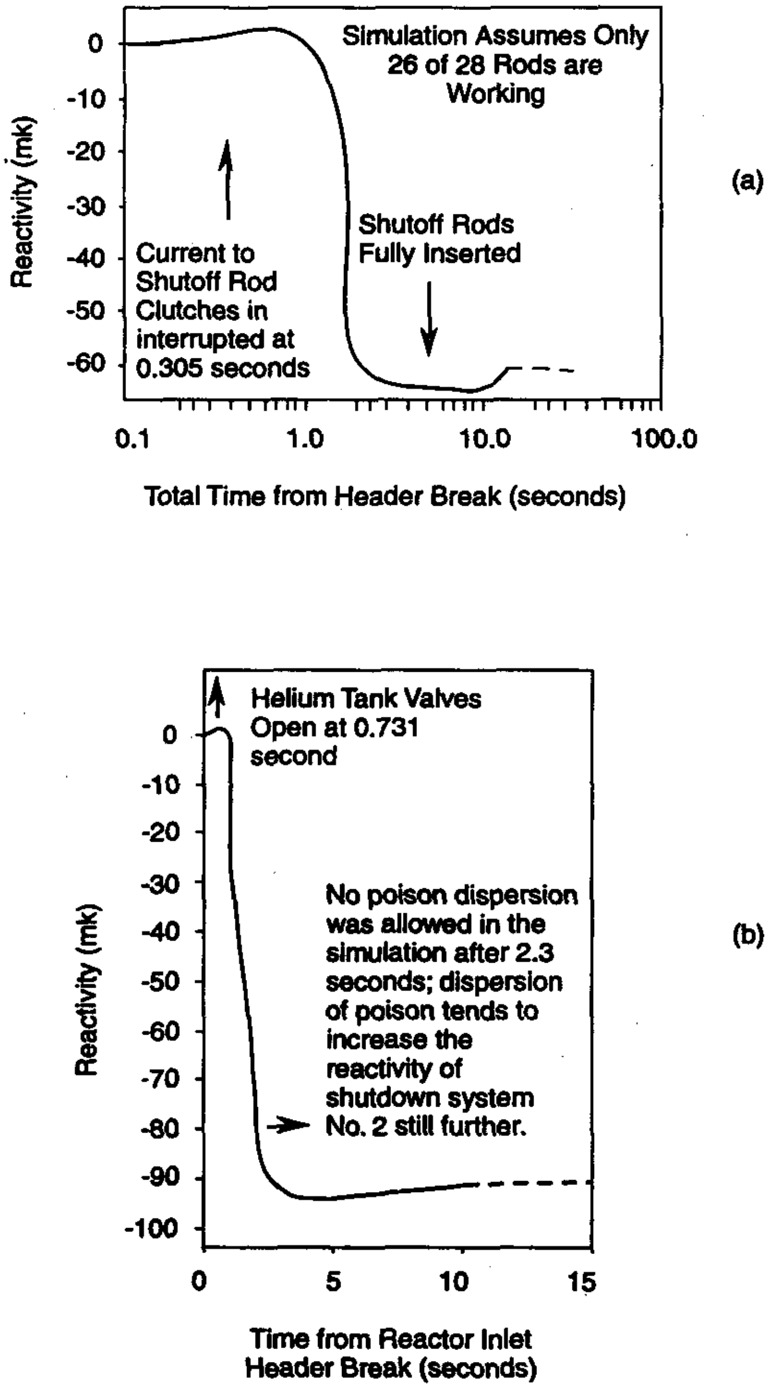

Figure 13.1: Reactivity transients following (a) shutoff rod insertion and (b) poison injection in CANDU 600. (The initial rise in reactivity shown is due to the fact that the calculation started with a header break causing reactivity to increase.)

Disadvantages

i) In some of the earlier plants, there was insufficient negative reactivity to ensure a long-term shutdown. Rods provided the initial drop and then, if recovery from the trip was not possible, moderator poisoning was required to ensure continued shutdown.

ii) This is a complex system (relative to moderator dump) and is subject to mechanical failure.

b) Poison injection

Poison injection

Poison (gadolinium) is injected into the moderator under high pressure. This causes a large reduction in the thermal utilization.

Advantages

i) Rapid insertion of reactivity coupled with great shutdown depth. Figure 13.1(b) shows reactivity versus time for a CANDU 600 injection system. Note that about – 95 mk is injected in 3 seconds.

Disadvantages

i) Poison must be removed from the moderator by ion exchange which is costly and slow (about 12 hours). If the reactor is shut down by poison injection, a xenon poison-out will occur before moderator poison can be removed.

ii) Requires careful control of moderator chemistry so that when the gadolinium nitrate is injected, it will not precipitate.

iii) There is no direct indication of the readiness of the shutdown system available to the operator in the control room (the current procedure is manual sampling for subsequent analysis in the chemistry lab).

oderator dump

c) Moderator dump

In some of the older plants, moderator dump is used as a backup for the shutoff rods.

Advantages

i) Simple, fail safe with gravity system.

ii) Absolute shutdown is guaranteed; with the moderator dumped, the core cannot be made critical.

Disadvantages

i) Slow for a large reactor. Figure 13.2 shows reactivity versus time for moderator dump at Pickering A. Note that in the first two seconds only -2 mk of reactivity has been inserted.

ii) The time required to pump the moderator back into the calandria is so long in a large reactor (typically around 50 minutes) that a poison out is very likely.

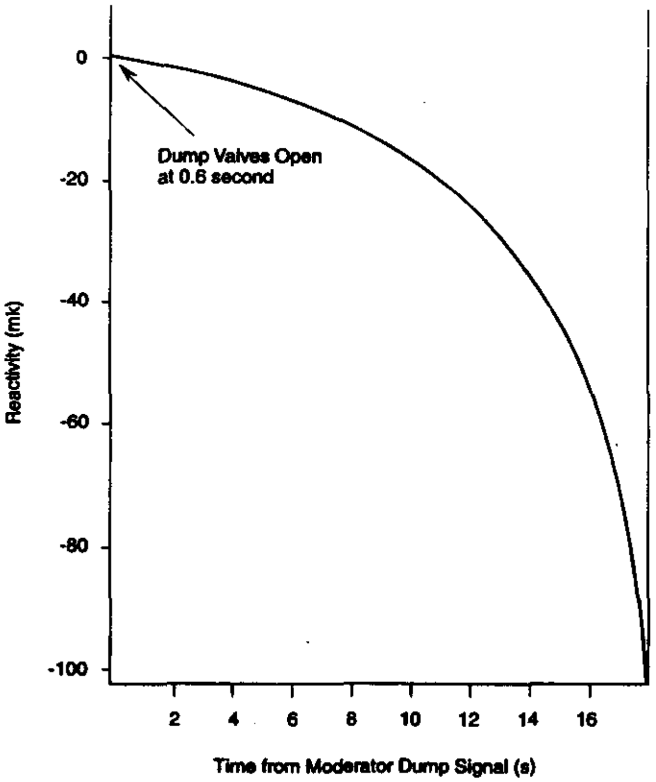

Figure 13.2: Reactivity transient following a moderator dump

13.7 FACTORS AFFECTING CONTROL ROD WORTH

The reactivity change produced by a control rod depends on a number of factors, including:

i) the location of the rod (for instance, whether it is near the centre of the core or its edge).

ii) the degree of insertion of the rod into the core.

iii) the interaction of the rod with the other rods present in the core.

These three aspects are considered in the following sections.

13.7.1 Dependence Of Control Rod Worth On Position Of Rod In Core

ependence of control rod worth on osition

A control rod is typically a cylindrical rod made of some material with a high absorption cross-section for thermal neutrons, for example, boron in stainless steel. The *worth* of a control rod is the reactivity change produced when the rod is inserted in the reactor. This depends, among other things, on the position of the rod in the core. First, let's consider the worth of a single shutoff rod inserted into the high-flux region at the centre of the core (Figure 13.3). Since the rod is an effective absorber of neutrons, the thermal flux in the region around it goes down significantly. If the reactor is to continue operating at the same bulk power with the rod inserted, the regulating system has to compensate for the decreased flux in the central region by raising the flux in the outer regions, as shown in Figure 13.4. The result is to displace the flux towards the edge of the core, which will lead to a greater thermal neutron leakage.

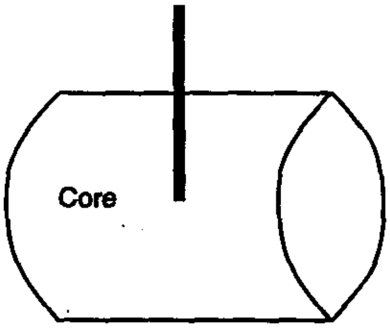

Figure 13.3: Control rod inserted into central core region

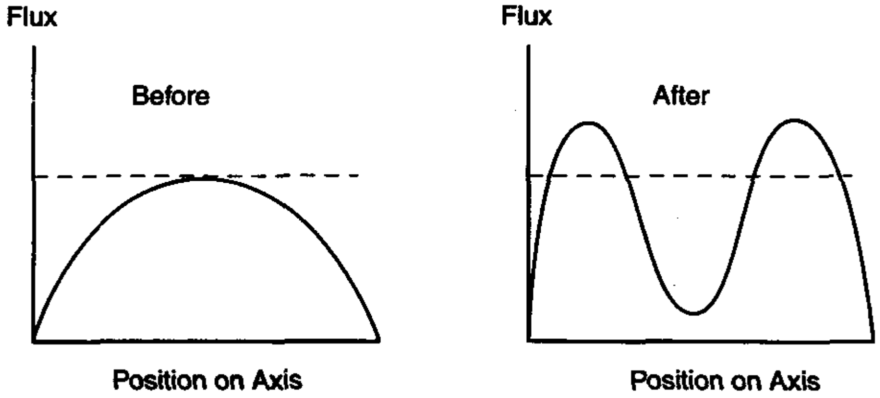

Figure 13.4: Thermal flux shape before and after insertion of rod

The worth of a rod therefore results from a combination of two factors: (1) increased neutron absorption in the region where it has been inserted, and (2) increased leakage caused by the flux distortion produced by the rod. The magnitude of each factor will depend on the placement of the rod in the core. Suppose that the rod is placed as shown in Figure 13.5. The absorption effect is obviously less than in the previous case because there are fewer neutrons to be absorbed when the rod is near the edge of the core. The regulating system therefore must increase the flux in the rest of the core by a relatively smaller amount to maintain bulk power (Figure 13.5). The flux distortion, and therefore the increase in neutron leakage, will also be less than when the rod was inserted into a high-flux region. The overall effect is that the rod worth will be considerably less than if it were in the central region.

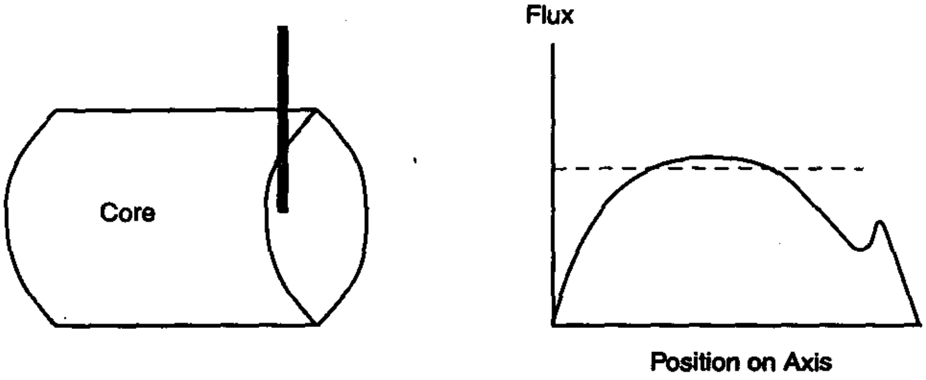

Figure 13.5: Thermal flux shape when rod is inserted near edge of core

13.7.2 Variation Of Rod Worth With Degree Of Insertion-The Differential Rod Worth

Let's examine how one would expect the reactivity effect of an adjuster rod to vary as it is gradually inserted into the reactor. We can describe this quantitatively by introducing a factor known as the ***differential rod worth***, which may be defined as the reactivity worth of, say, each extra millimetre of rod added to the core.

Differential rod worth

If we start with the rod completely withdrawn, the initial movement will produce relatively little effect, since the rod is entering a region where the neutron flux is quite small. As it enters further into the core, the ***differential*** worth (worth per millimetre) steadily rises, reaching a maximum as the leading end reaches the core centre. As the end of the rod progresses beyond that point, the differential worth decreases again, reaching a minimum at the fully inserted position.

The variation of the total reactivity worth of the rod, as a function of its position, is shown in Figure 13.6. The differential worth is represented by the slope of this curve, which, as you can see, is greatest when the end of the rod reaches the centre line of the core.

In passing, we might note that the partial movement of a rod or a bank of rods into the core will produce the same distortion of the thermal flux shape as described in the previous section, but in the vertical direction. The flux in the upper part of the core will be reduced relative to the flux in the lower part.

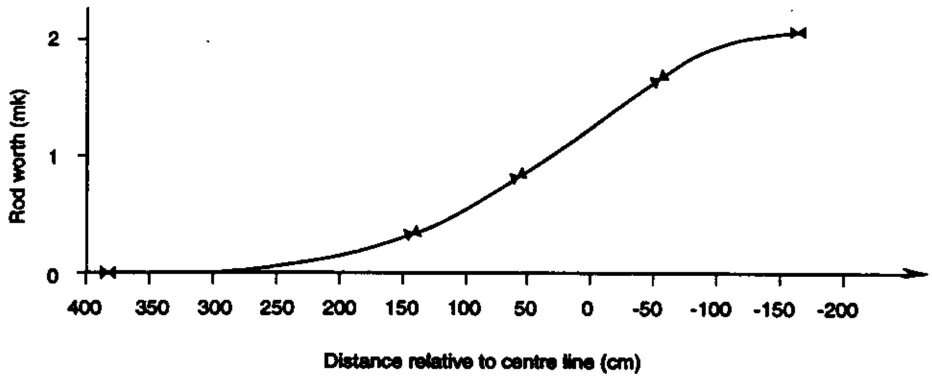

Figure 13.6: Reactivity worth of rod as a function of position

13.7.3 Interaction Of Rods With Each Other-Rod Shadowing And Antishadowing

ontrol rod interaction

The worth of a control rod placed in some location depends on whether the overall flux shape has already been distorted by inserting one or more other rods. To illustrate, suppose that we have inserted a single rod into a high-flux region of the core, as shown in the top portion of Figure 13.7. After the regulating system has compensated for the insertion of the rod, the flux shape will be distorted as shown.

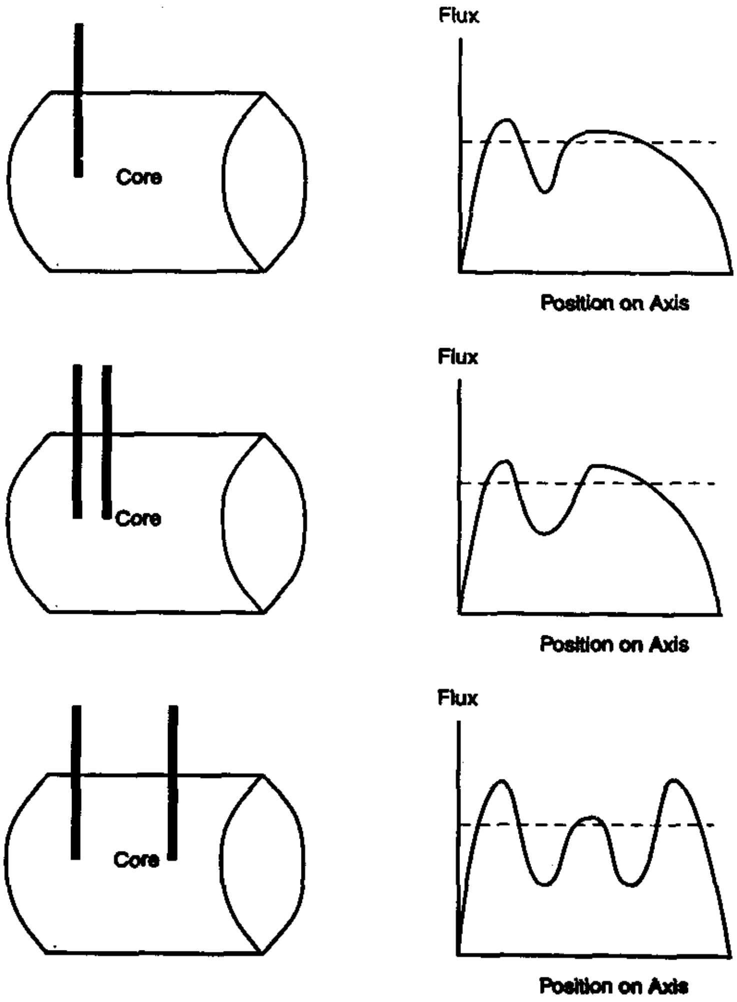

Figure 13.7: Rod shadowing and anti-shadowing

Suppose that we now insert a second identical rod quite close to the first one, as in the middle illustration in Figure 13.7. Since it will be entering a region where the flux has already been depressed by the first rod, it will absorb fewer neutrons than it could have if the other rod were not there. In addition, the presence of the second rod will reduce the flux in the neighbourhood of the first one, thereby reducing its worth compared to the situation where it was the only rod in the core.

Thus, if each rod on its own had a worth of, say, x mk, the worth of the two in combination will be less than 2x. The reduction in individual worth of each rod because another is nearby is known as ***rod shadowing***.

Rod shadowing

Consider now what would have happened if the second rod had been inserted into a region far away from the first one, for example, at the peak of the distorted flux distribution produced by the former, as in the bottom illustration in Figure 13.7. Because it is going into a region where the neutron flux has been increased by the action of the first rod, it can absorb more neutrons than if it were the only rod in the core. The combined worth of the two rods will then be greater than 2x. This increase in the worth of each rod due to the presence of the other is known as ***rod antishadowing***.

Rod antishadowing

ASSIGNMENT

1. Without looking at your notes, list the various sources of in-core reactivity change for which the reactivity mechanisms of the reactor will be required to compensate.

2. Write the six-factor formula. Identify the terms that can conveniently be adjusted to provide reactivity control, and list the practical ways of doing this.

3. Imagine that a Bruce reactor trips, inserting - 40 mk of reactivity. The heat transport system is maintained at normal operating temperature. Using the information in Table 13.2, would you expect the reactor to remain permanently shut down: (a) if it contains fresh fuel, and (b) if it contains equilibrium fuel?

4. How would the answers to the previous question be altered if the heat transport system were cooled down?

5. List three applications each for (a) boron and (b) gadolinium as soluble poisons.

6. Simple chemical analysis for boron or gadolinium is not considered sufficient to determine the reactivity worth of moderator poison. Explain why.

7. Discuss the advantages and disadvantages of moderator dump, shutoff rods and poison injection for reactor shutdown.

8. Could the state of the fuel (that is, fresh or equilibrium) make any difference to the ability of the reactor to override xenon? Explain your answer.