Module 12

Reactivity Effects Due to Temperature Changes and Coolant Voiding

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12.1 MODULE OVERVIEW

When the reactor operates at power, any change in power level will generally alter the temperatures of the fuel, moderator and coolant. A change in the temperature of any of these components will cause a change in ***reactivity*** which will, in turn, affect the reactor's operating conditions. The magnitude of this ***feedback*** is specified by quoting the value of the ***temperature coefficient of reactivity*** (in μk/°C) for each of the three reactor components.

Temperature coefficient of reactivity

We begin by reviewing the principal physical mechanisms which give rise to the temperature coefficients. These are (a) ***Doppler broadening*** of the U-238 resonances; (b) changes in the energy distribution of thermal neutrons as the temperature increases (***spectrum hardening***); (c) density changes of the coolant and moderator with temperature. The overall temperature coefficient of a given reactor component (for instance, fuel) can be regarded as the sum of the individual temperature coefficients of each term in the six-factor formula for the multiplication factor. We describe how the sign of each relevant coefficient can be explained in terms of the physical mechanisms discussed earlier. This is done for both fuel and moderator coefficients as well as for fresh and equilibrium fuel.

Finally, we look at some of the operational implications of temperature coefficients, including the changes of reactivity that occur on startup and shutdown, and the importance of the Doppler effect in providing negative feedback to limit the consequences of positive power transients.

Void formation

The effects of ***void formation*** are also an important source of feedback in power transients. We consider the reasons for the positive reactivity effect of ***voiding channels*** in reactors using heavy water as coolant, and associated practical implications such as the need to maintain a high coolant isotopic.

12.2 MODULE OBJECTIVES

After studying this module, you should be able to:

i) Define the temperature coefficient of reactivity.

ii) Explain, in general, the desirability of a negative temperature coefficient of reactivity.

iii) Describe the ***Doppler effect*** in the fuel.

iv) Explain what is meant by ***spectrum hardening***, and how this might be expected to affect the value of η in both fresh and equilibrium fuel.

v) Discuss the effect on reactivity of changes in moderator or coolant density.

vi) Explain why the fuel temperature coefficient is negative, and why its value changes significantly from fresh to equilibrium fuel.

vii) Explain why, ***in practice***, the moderator temperature coefficient is positive for both fresh and equilibrium fuel.

viii) Given temperature coefficients for all three components of the reactor, calculate the expected change in reactivity from one operational state to another (given the temperature of each component for each state).

ix) Explain why the fuel temperature coefficient is more important than the others in limiting power transients.

x) Define the ***power coefficient*** and give a typical range of values for a CANDU.

xi) Explain why ***coolant voiding*** leads to a positive reactivity in CANDU reactors, and why excessive positive ***or*** negative void coefficients are undesirable in reactor operation.

12.3 TEMPERATURE COEFFICIENT OF REACTIVITY

In the module on reactor kinetics (Module 8), we ignored any variations in reactivity ***due to changes in power***. As we saw in Module 11, there are marked changes in reactivity due to xenon, which occur over a period of minutes to hours after an overall power change. Changes in reactor power also cause changes in the temperature of the fuel, moderator, and coolant. These too have an effect on reactivity—an effect which acts on a much shorter time scale than the xenon. We begin by discussing an experiment which demonstrates the importance of these feedback reactivity effects.

In 1949, the NRX reactor at AECL, Chalk River, was allowed to "run away". NRX was a heavy water moderated reactor which used control rods for reactor regulation. The heavy water level was set somewhat above the height at which the reactor would be critical at low power with the rods withdrawn. Reactor power was allowed to increase unchecked, and the manner in which it increased is rather unexpected (see Figure 12.1).

The power initially increased exponentially with a period of 33 seconds ($\tau = 33$ s, $\Delta k = +1.6$ mk). As the temperature of the fuel rods increased, however, the reactivity decreased and this caused the rate of power increase to slow. Later, the reactivity decreased at a faster rate as the heavy water became warmer. The total decrease in reactivity was enough to make the reactor subcritical, and the end result was that the power reached a maximum value and then started to decrease.

Thus the reactor was self-regulating, since temperature changes induced by a power increase reduced reactivity and so prevented power from increasing indefinitely. Of course, in this experiment, the initial excess reactivity was quite small; if more reactivity had been inserted at the start, it is quite possible that the power would have continued to rise.

Self-regulating reactor

The temperature coefficient of reactivity is defined as the change in reactivity per unit increase in temperature. Its units are mk/°C or µk/°C (1 µk = 10^{-3} mk). The coefficient may be positive or negative. In the example just described, it was negative because an increase in temperature led to a loss of reactivity.

Mathematically the ***temperature coefficient*** is written

$$\frac{1}{k}\frac{dk}{dT}$$

Temperature coefficient

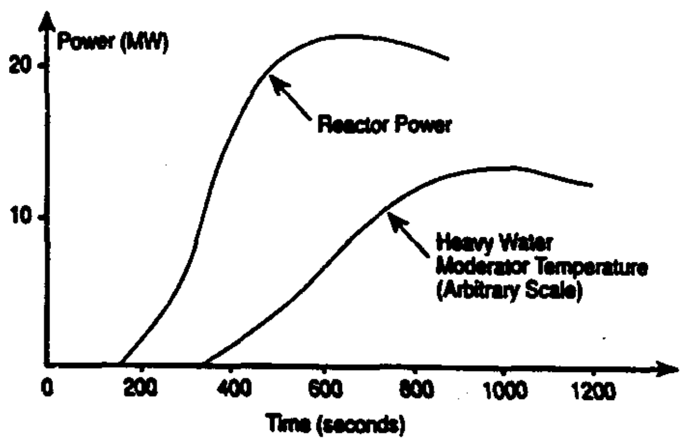


Figure 12.1 : Self-regulation characteristics of NRX reactor

Temperature changes occur in the fuel, coolant and moderator more or less independently, and there will therefore be a temperature coefficient of reactivity associated with each. It is very desirable for the overall temperature coefficient of a reactor to be negative to provide the self-regulating feature illustrated by NRX. It is particularly advantageous if the fuel coefficient is negative because in a transient the fuel will heat up more rapidly than other components of the core.

12.4 PHYSICAL BASIS FOR TEMPERATURE COEFFICIENTS

In a later section, we look at the individual temperature coefficients of the fuel, moderator and coolant, and we describe the effects of temperature on the terms in the six-factor formula. Before we do this, it is useful to consider the physical basis for some of the more significant contributions to the temperature coefficients. In the following sections, we look at three particularly important effects.

We can see how each of these effects influences the factors in equation (3.7) for the reaction rate (R) in the reactor for a given nuclide

$$R = \phi\Sigma = \phi N\sigma$$

where σ refers to either the fission or the absorption cross-section, as appropriate.

The three effects considered include:

1. Doppler broadening in the fuel, which increases the absorption of neutrons in the resonance region of the U-238 microscopic cross-section;

2. Changes in the energy spectrum of the thermal neutron flux, which affect the microscopic cross-sections for the various scattering, absorption and fission processes;

3. Density changes which directly affect N, the number density of the nuclides present in the reactor.

12.4.1 Doppler Broadening In The Fuel

Doppler effect

The ***Doppler effect*** arises directly from a temperature change in the ***fuel***. A rise in fuel temperature increases the resonance capture in U-238 for the following reason. We know that the absorption cross-section of U-238 in the resonance region consists of a set of fairly sharp peaks of the sort shown in Figure 12.2, where the probability of a neutron being absorbed depends critically on the exact value of its kinetic energy or, what amounts to the same thing, the speed at which the neutron is moving. Actually, it's more complicated than that because the important factor in determining the probability of absorption is the speed of the neutron ***relative to the U-238 nucleus***. Since heating the fuel will make the atoms of U-238 vibrate more vigorously, it isn't surprising that it has an effect on the relative speeds of the neutrons and the U-238 nuclei, consequently changing the shape of the peak.

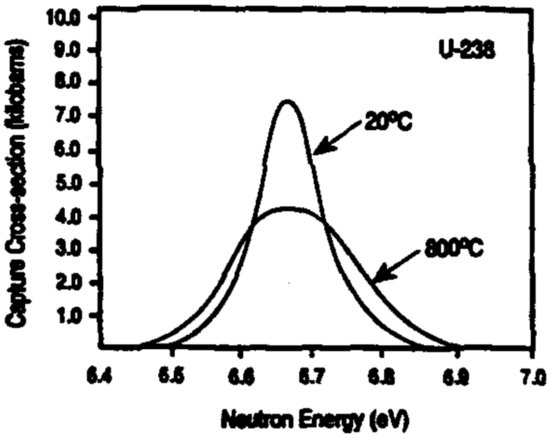
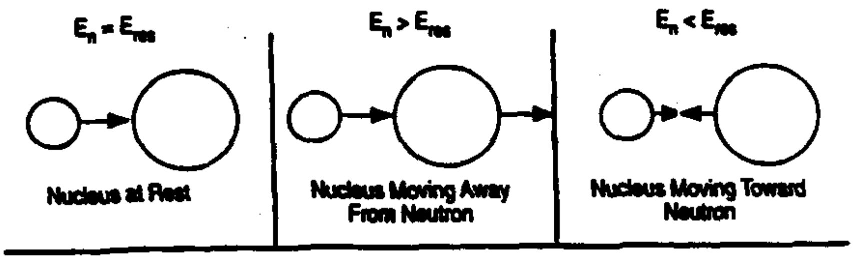


Figure 12.2: Doppler broadening of U-238 resonance



Note: Here E_n represents the kinetic energy of the neutron and E_{res} the energy at the peak of the resonance. All three neutrons appear to the nucleus as having the resonance energy.

Figure 12.3: Mechanism of Doppler broadening

To illustrate, consider a nucleus at rest, as shown at the left of Figure 12.3. A neutron that happens to have a speed corresponding to the peak of the resonance will have a high probability of being absorbed, while one that is travelling slightly slower or faster will have a much reduced probability. Now think about what happens when the fuel is heated and the U-238 nuclei are vibrating back and forth. A neutron whose speed is such that it previously lay well outside the peak may encounter a U-238 nucleus that is moving at that instant in such a way that the speed of the neutron ***relative to the nucleus*** coincides with the peak. The centre diagram in Figure 12.3 shows a neutron whose speed is above where the peak would be located if the U-238 nucleus were at rest, but which encounters a nucleus moving in the same direction at a speed that makes the neutron's speed of approach the same as it was in the first diagram. To the nucleus, this neutron would appear to be within the peak of the resonance. The same thing could happen to a neutron whose speed is such that it would be below the peak when the nucleus was at rest, but which happens to encounter a "hot" uranium nucleus moving towards it at exactly the right speed (right-hand diagram).

Resonance broadening

The net result of heating the fuel is therefore that the resonance can be considered as being "broadened" as shown in Figure 12.2. Although the height of the peak has been reduced (because neutrons that were originally moving at exactly the correct speed for the peak are no longer moving at the correct speed), the U-238 cross-section is in any case so high that any neutron within the overall peak region is virtually certain to be absorbed in the fuel (the mean free path in fuel of a neutron at the energy of the peak is about 0.025 mm). The net effect of heating is to broaden the range of energies over which the neutrons have a high probability of being absorbed. When the fuel is heated, therefore, there will be a reduction in the resonance escape probability (p) and consequently in the reactivity.

12.4.2 Changes In Neutron Energy Spectrum

An alteration to the temperature and/or density of any component of the reactor affects the energy distribution of the neutrons (the ***energy spectrum***). This, in turn, changes the fission and absorption rates in other components, owing to the fact that these are sensitive to the neutron energy.

Thermal neutrons

We know that neutrons in the reactor start off at a high energy (up to several MeV) and then bounce around in the moderator until they reach relatively low speeds where they are ***in thermal equilibrium*** with their surroundings. At this point, they are as likely to gain energy in a collision with a nucleus as they are to lose energy.

Thermal neutrons are characterized by a distribution of energies, described by a rather complicated mathematical expression known as the ***thermal energy spectrum*** (Figure 12.4.). At room temperature, the most probable value for a thermal neutron energy is 0.0253 eV. Since the kinetic energies of the atoms of any material depend on its temperature, changes in the temperature of the moderator, coolant or fuel will affect the neutron spectrum, and thus the average thermal neutron energy. Figure 12.4 shows the shift in the spectrum for a change in moderator temperature from 20°C to 300°C. The average neutron energy is proportional to the ***absolute*** temperature of the moderator, so it is approximately doubled by going from 293 K to 573 K. This move towards higher neutron energies is often referred to as an increase in the ***neutron temperature***.

Neutron temperature

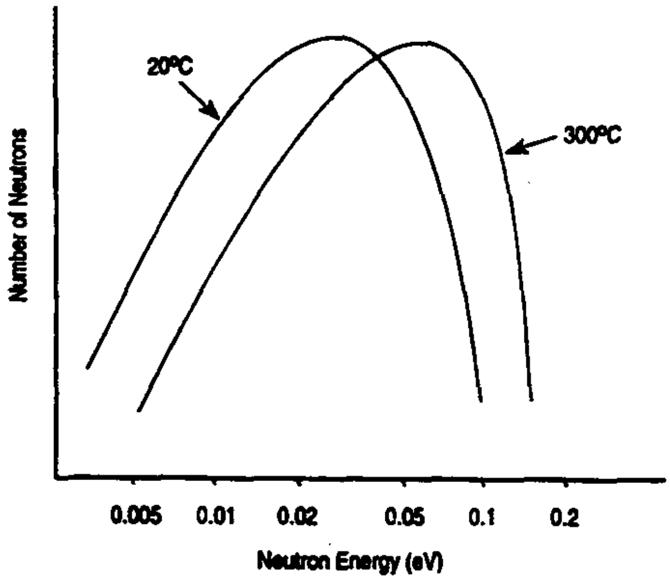


Figure 12.4: Neutron energy shift with changing moderator temperature

The change in the thermal neutron spectrum with temperature will alter the balance between the fission and absorption rates in the core, because the fission and absorption cross-sections are both functions of the neutron energy. The parameter chiefly affected is the reproduction factor (η) as discussed below.

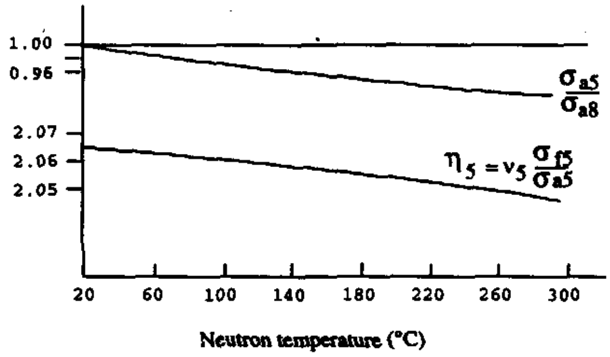


Figure 12.5: Deviation of absorption(°C) -section of U-235 from l/v, and variation of η_5, with moderator temperature. (Upper curve normalized so that ratio = 1 at 20°C)

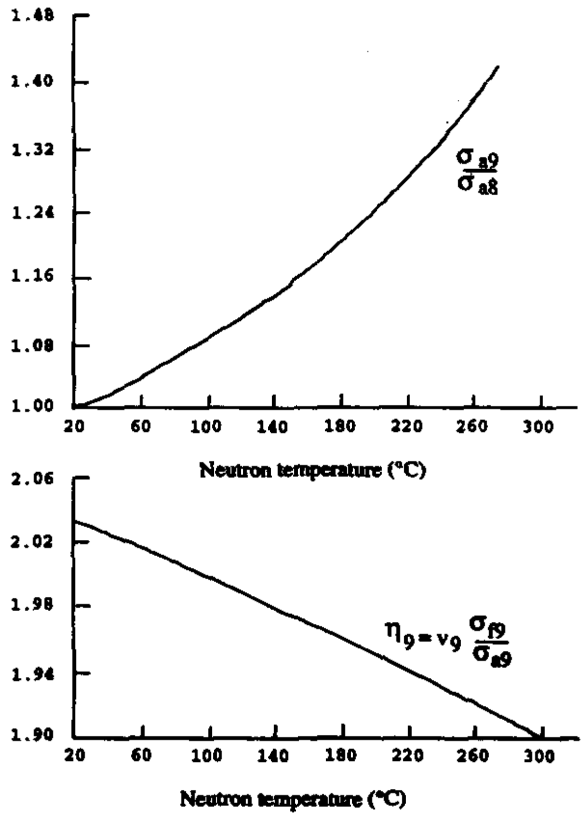


Figure 12.6: Deviation of absorption cross-section of Pu-239 from l/v, and variation of η_9, with moderator temperature (Upper curve normalized so that ratio = 1 at 20°C)

Variation of η with neutron energy

As mentioned in Section 3.8, many of the materials in the reactor have absorption cross-sections which vary inversely with the neutron speed, that is, $\sigma_a \propto 1/v$. If *all* materials exhibited the same l/v dependence on neutron speed (or energy), the ***relative*** reaction rates would be unaffected by a change in neutron temperature. However, both U-235 and Pu-239 have absorption cross-sections which depart significantly from l/v behavior. One way to illustrate this is to plot the ratio of the absorption cross-section of each isotope to the absorption cross-section of U-238, which *is* approximately l/v, as a function of neutron temperature. The departure of the absorption cross-sections of U-235 and Pu-239 from l/v is illustrated by the upper curve in Figures 12.5 and 12.6 respectively. It can be seen that the absorption rate of U-235, relative, for example, to the U-238 which forms the majority of the fuel, will drop as the neutron temperature increases. For Pu-239, on the other hand, an increase in neutron temperature will cause a marked increase in the absorption rate of Pu-239 relative to the l/v absorbers. This increase is due to the movement of neutrons at the higher end of the thermal spectrum into the large resonance at 0.3 eV in Pu-239 (see Figure 12.7).

Unfortunately, the situation is more complicated than this, because the fission and absorption cross-sections of each fissile isotope vary ***in a different way*** with neutron energy. Consequently, knowing how absorption in the fissile isotopes changes with temperature does not, by itself, explain how η behaves. The most convenient way to illustrate this is to look at the values of η for each material, considered as an individual isotope; for instance, the η-value for U-235, η_5, is defined as $\eta_5 = \nu_5 \times (\sigma_{f5}/\sigma_{a5})$, by analogy with the definition of η in the six-factor formula (equation 5.4) which applies to the fuel as a whole. The variation of the η-values of U-235 and Pu-239 is shown in the lower curves in Figures 12.5 and 12.6. Over the range shown, each isotope demonstrates a decrease in η with increasing neutron temperature, the decrease of Pu-239 being much steeper.

Notes & References

We can now look at what we would expect to happen to the overall η-value of the fuel, which is equal to the number of fission neutrons produced per thermal neutron absorbed in the fuel (where "fuel" includes U-238, fission products, etc.). For a freshly-fuelled reactor, the situation is fairly straightforward. As the neutron temperature increases, the neutron absorption rate in U-235 will decrease relative to the l/v components of the fuel, such as U-238. In addition, the decrease of η_5 with neutron temperature means that the absorptions which do take place in U-235 will be less effective in causing fissions. Consequently, it is clear that the contribution of U-235 to the temperature coefficient of η will be negative, so that in a freshly-fuelled core $d\eta/dT$ will also be negative.

In an equilibrium core, U-235 will still, of course, make a negative contribution to the temperature coefficient of η. For the Pu-239 which is now also present, the pronounced increase of the absorption cross-section with temperature will lead to a marked increase in absorptions in Pu-239 relative to the other components of the fuel. On the other hand, the decrease of η_9 will make these absorptions less effective in causing fissions. It turns out, in practice, that the former effect predominates, so that the contribution of Pu-239 to the overall temperature coefficient of η is positive. The magnitude of this positive contribution is such that, for equilibrium fuel, it predominates over the negative U-235 contribution, so that the overall $d\eta/dT$ for equilibrium fuel is positive.

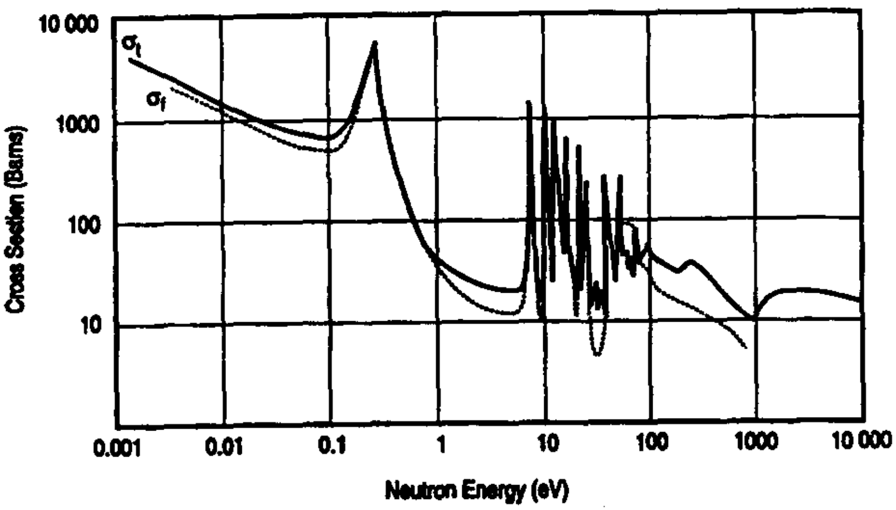


Figure 12.7: Fission and total ($\sigma_t = \sigma_a + \sigma_s$) cross-sections of Pu-239

12.4.3 Density Changes

Density effects

As the temperature of the moderator or coolant increases, its density will decrease. Since the number of atoms per unit volume decreases, neutrons will travel further between collisions and therefore have an increased chance of leaking out of the reactor. Both the fast and thermal non-leakage probabilities will consequently decrease, tending to lower the reactivity. On the other hand, the reduction in atomic density will lower the ***macroscopic*** absorption cross-section of the moderator or coolant, which will increase the thermal utilization (f), thus tending to increase reactivity. For the moderator, the effect of the reduction in atomic density will be particularly strong if it contains an appreciable quantity of poison. It will therefore be most pronounced for a fresh core, where a significant quantity of poison is required to compensate for the high inherent reactivity.

12.5 TEMPERATURE COEFFICIENTS FOR FUEL, MODERATOR AND COOLANT

12.5.1 General Expression For Temperature Coefficient

As stated in Section 12.3, the temperature coefficient is defined in general as the change in reactivity per unit (°C) change in temperature, that is,

$$\frac{dk/k}{dT} = \frac{l}{k}\frac{dk}{dT}$$

where the multiplication factor is given by the formula (Section 5.4)

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

It can be shown mathematically that

(12.1)

$$\frac{l}{k}\frac{dk}{dT} = \frac{l}{\varepsilon}\frac{d\varepsilon}{dT} + \frac{l}{p}\frac{dp}{dT} + \frac{l}{\eta}\frac{d\eta}{dT} + \frac{l}{f}\frac{df}{dT} + \frac{l}{\Lambda_f}\frac{d\Lambda_f}{dT} + \frac{l}{\Lambda_t}\frac{d\Lambda_t}{dT}$$

which means that we can obtain the overall temperature coefficient by adding the contributions of the six factors in the formula.

Notes & References

12.5.2 The Fuel Temperature Coefficient Of Reactivity

Fuel temperature coefficient

The fuel temperature coefficient arises principally from two factors: one is the Doppler effect and the other the effect due to the fact that the neutron spectrum is slightly hardened by the increase in fuel temperature. For fresh fuel, the contributions from changes in p and η are both negative, the predominant one being the reduction in p due to the Doppler broadening. For equilibrium fuel, the strong negative Doppler contribution is partly compensated by the fact that the ***coefficient of η is positive***, owing to the presence of Pu-239, as discussed in Section 12.4.2. Calculations of the fuel temperature coefficient in a typical CANDU yield the following values:

Fresh fuel: Fuel temperature coefficient $= -15$ μk/°C

Equilibrium fuel: Fuel temperature coefficient $= -4$μk/°C

12.5.3 The Moderator Coefficient Of Reactivity

Moderator coefficient

The main effects produced by heating the moderator are (a) a decrease in moderator density, and (b) an increase in the average neutron energy. The temperature of the moderator affects the neutron temperature much more than the temperature of the fuel or the coolant does, since the moderator is principally responsible for thermalizing the neutrons in the first place.

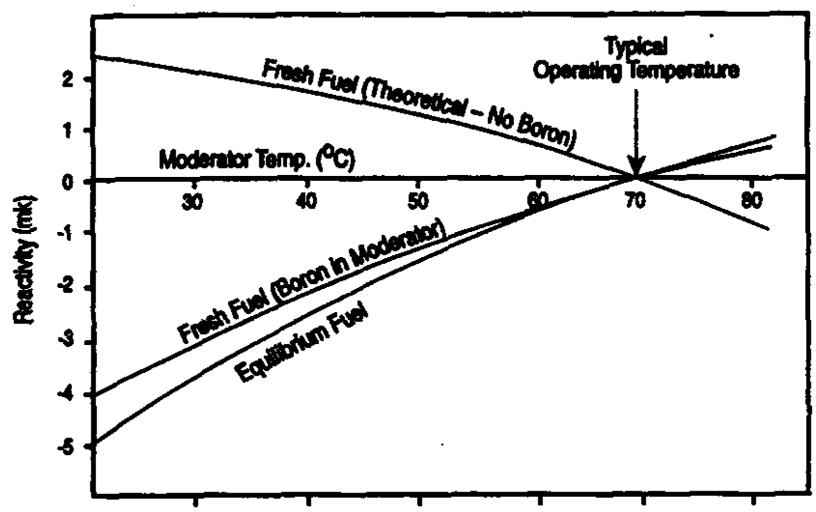


Figure 12.8: Change in reactivity with moderator temperature

For both fresh and equilibrium fuel, calculations show that p decreases with an increase of moderator temperature (which decreases moderator density and so increases the distance a neutron travels while it is slowing down). Fast and thermal leakage both increase for the same reason. The thermal utilization makes a positive contribution because of the decrease in moderator absorption at the lower moderator density. The important difference between the fresh and equilibrium fuel cases is that the coefficient of η is strongly negative for fresh fuel and strongly positive for equilibrium fuel as indicated in Section 12.4.2. The result is that, while the calculations predict a strong negative moderator temperature coefficient for fresh fuel, the coefficient for equilibrium fuel is positive. This may be seen by comparing the upper and the lowest curves in Figure 12.8 (the coefficient is given by the ***slope*** of the line in each case). It should be noted, however, that the calculations for the freshly fuelled core ***do not include the effect due to the boron*** which in practice must be added to the moderator to hold down the reactivity of the fresh core.

The reduction in the density of the ***poisoned*** moderator produces a large increase in thermal utilization (f) when the moderator is heated. This increased contribution is sufficient to change the sign of the overall moderator coefficient from negative to positive. This effect is shown by the third curve in Figure 12.8. The approximate values of the moderator coefficient (over the range 40°C to 70°C) are:

Fresh fuel: (no boron in moderator)	=	−15	μk/°C
Fresh fuel: (poisoned moderator)	=	+70	μk/°C
Equilibrium fuel:	=	+90	μk/°C

While the first case has no practical significance for the operating reactor, it is interesting in that it shows the significance of the change in sign of the coefficient of η in going from fresh to equilibrium fuel.

12.5.4 The Coolant Coefficient Of Reactivity

Coolant coefficient

The reactivity effect associated with a change in coolant temperature is more complicated in its make-up than the other two coefficients we've been considering, so that we won't discuss this in detail. The calculated effect of changing the coolant temperature in a CANDU 600 is shown in Figure 12.9. The coefficient for the equilibrium fuel case is positive throughout the whole temperature range but, for reasons that are too complex to explain here, the coolant coefficient with fresh fuel starts off negative but changes to positive at a coolant temperature of about 250°C. (The coefficient, again, is given by the *slope* of the curve at any point).

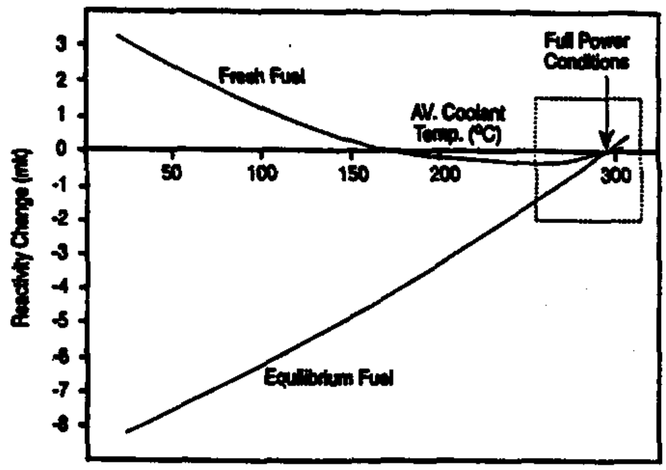


Figure 12.9: Change in reactivity with instantaneous change in coolant temperature (calculated for CANDU 600)

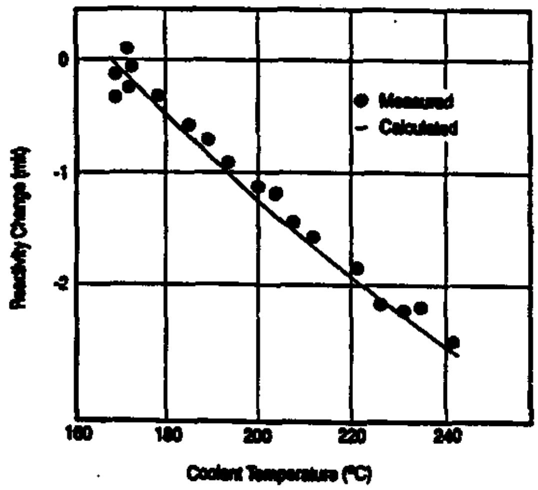


Figure 12.10: Comparison of measured and calculated reactivity changes due to fuel and coolant temperature changes in Pickering A (fresh fuel)

It is difficult to determine the coolant coefficient from measurements on the reactor, because you can't change the coolant temperature without simultaneously changing the fuel temperature. It is possible to get an overall check on the calculation methods by measuring reactivity as the coolant and fuel are heated simultaneously. Figure 12.10 demonstrates a comparison of theory and measurement for Pickering A. The heat transport system was heated by running the primary pumps while the reactor was held critical at low power. Since the heating took place slowly, one can assume that the fuel temperature kept in step with the coolant. The results were therefore a combination of the fuel and coolant coefficients. It can be seen that there is good agreement between the calculated and measured reactivity changes.

12.6 PRACTICAL ASPECTS OF REACTIVITY VARIATION WITH TEMPERATURE

We have already mentioned that it is desirable for the temperature coefficients to be negative so that a self-regulating feature is provided. We must, however, consider more than just the values of the three temperature coefficients. Two very important factors are (a) the magnitude of the temperature changes that take place in each component for a given power change, and (b) the time taken for each component to heat up.

TABLE 12.1

Typical temperatures of reactor components (°C)

Component	Cold Shutdown	Hot Shutdown	Full Power
Fuel	25	290	690
Coolant	25	265	290
Moderator	25	70	70

The typical temperatures of the reactor components for three "standard" conditions are provided in Table 12.1. Variations in overall reactivity as a CANDU 600 is taken from cold shutdown to full power are illustrated in Figure 12.11 for the fresh fuel and equilibrium fuel cases. With equilibrium fuel, the net reactivity change in going from cold shutdown to full power is less than 2 mk. For fresh fuel, however, there is a loss of about 8.5 mk in moving from cold to hot shutdown and a further loss of 6.5 mk in going from hot shutdown to full power. Since the reactor will regain this reactivity when it is shut down again, allowance must be made for this when estimating the amount of negative reactivity that must be inserted to keep the system safely subcritical even after complete cooling has taken place. Care must also be taken in going from cold shutdown to hot shutdown with an equilibrium core because of the reactivity *gain* of about 3 mk that occurs during the change.

Notes & References

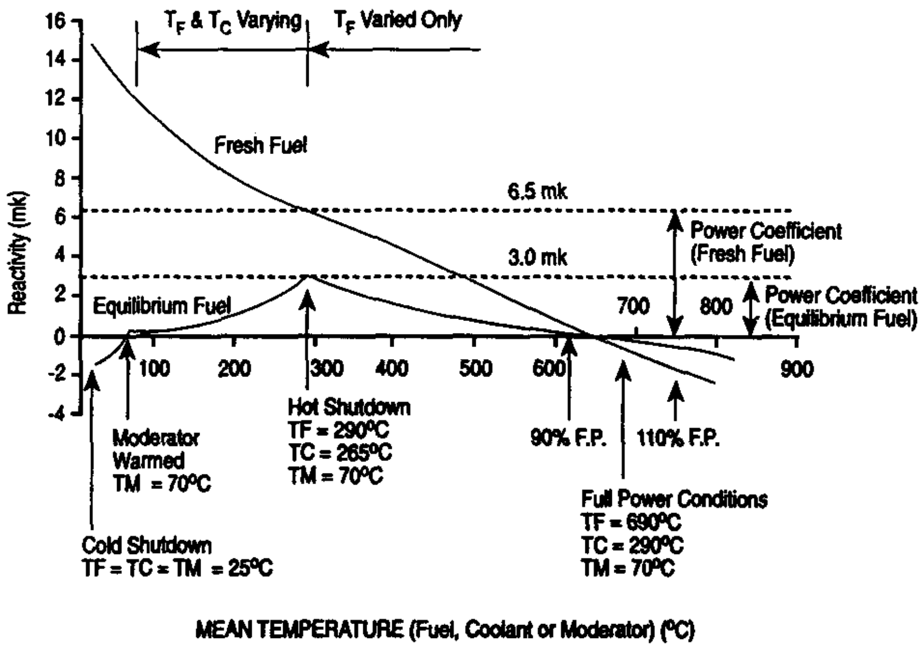


Figure 12.11: Reactivity changes with temperature of reactor components

The change in reactivity involved in moving from the hot shutdown to the 100% power condition is known, somewhat confusingly, as the ***power coefficient***. Remember that this "coefficient" is the ***total*** reactivity change between the two states rather than the reactivity change per °C, as was the case for the other coefficients we discussed earlier. Note also that the power coefficient only includes the reactivity effect of the temperature changes and not any reactivity loss due to fission product formation. As mentioned above, the magnitude of the power coefficient for a CANDU is typically in the order of -3 to -6 mk.

Power coefficient

If the temperature coefficients and temperature changes for each component are provided, it is easy to calculate the overall reactivity change in going from one condition to another. For example, let's estimate the loss of reactivity in going from cold shutdown to full power with fresh fuel. The values of the three temperature coefficients involved, averaged over the appropriate temperature ranges, are assumed to be

Fuel coefficient:	-15 µk/°C
Coolant coefficient:	-30 µk/°C
Moderator coefficient:	$+75$ µk/°C

Taking the temperature values in Table 12.1, we can calculate the expected reactivity change in moving from cold shutdown to full power by multiplying each coefficient by the appropriate temperature change and taking the sum, or,

$$\Delta k = (-15 \times 665) + (-30 \times 265) + (+75 \times 45)\ \mu k$$

$$= (-10.0 - 8.0 + 3.4) \times 10^3\ \mu k$$

$$= -14.6\ mk$$

This agrees well with the curve shown in Figure 12.11.

In a power transient, the temperature rise of the fuel will be much larger and will occur much more rapidly than that of the coolant. In fact, the fuel temperature will change almost instantaneously, while the coolant temperature change will lag behind the power change by a few seconds. The desired self-regulation will therefore be achieved merely by having a negative fuel temperature coefficient, which fortunately is the case for both fresh and equilibrium fuel.

12.7 EFFECTS DUE TO VOID FORMATION

Voids will be formed if the moderator or the heat transport system fluid boils. Void formation is more likely to occur in the coolant than in the moderator, so we'll restrict our discussion to the effects of loss of coolant.

Because reactivity increases with loss of liquid coolant, knowledge of the magnitude of this effect is important for safety reasons. The possible causes of coolant boiling are

Low pressure (pipe rupture, pressurization system failure)

Low flow (blockage, pipe rupture, pump failure)

Excess power (flux distortion, regulating system failure)

Under these circumstances, the coolant will gradually be displaced by steam and eventually the channel(s) will become totally depleted of liquid coolant. This is frequently called ***voiding the channel.***

Effects of voidage

Voiding the fuel channel causes a decrease in the moderation of neutrons in the immediate neighbourhood of the fuel elements. Looking at Figure 12.12, you can see that a neutron born in one fuel element (for instance, element A) normally passes through some coolant before reaching the next fuel element (element B) with the coolant providing a little moderation. When the channels are voided, there is no moderation so that higher energy neutrons interact with the fuel in element B.

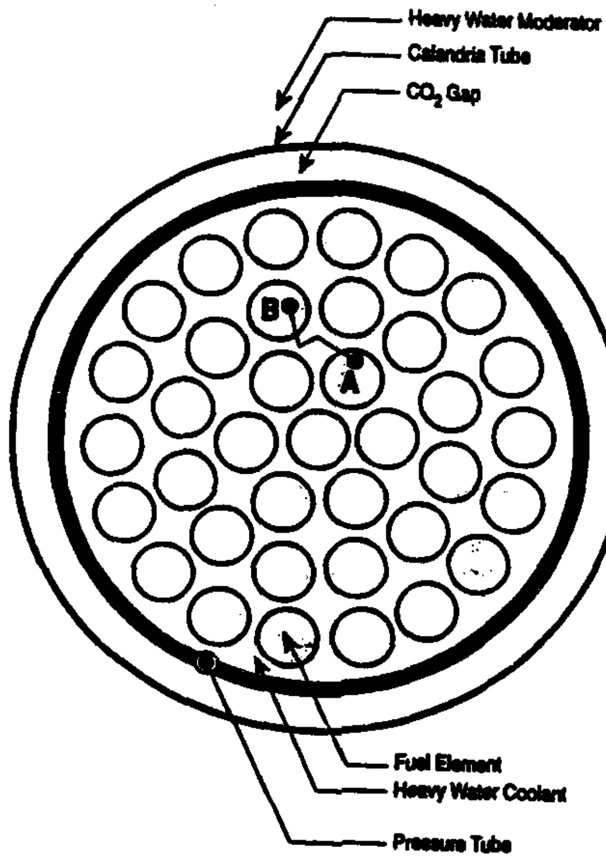


Figure 12.12: Disposition of moderator and coolant round fuel bundle

This has two principal effects, both related to the U-238 content of the fuel. Since fission neutrons suffer very little energy loss in moving from one fuel element to another, we are primarily interested in the cross-sections of U-238 at high energies. Figure 12.13 shows how the radiative capture and fission cross-sections of U-238 vary with neutron energy. The removal of coolant produces the following effects:

a) An increase in the fast fission factor (ε), since fission neutrons have an increased chance of interacting with U-238 while still above the threshold energy for fission;

b) An increase in the resonance escape probability (p) because fewer fission neutrons are slowed down into U-238 resonances before they escape from the fuel bundle.

Another effect, less important than those above, is caused by a change in the thermal neutron spectrum. The removal of hot coolant ***reduces*** the thermal neutron temperature. The result is a change in η, as discussed in Section 12.4.2. In this case, since we are dealing with a ***decrease*** in neutron temperature, the contribution to the void reactivity will be positive for fresh fuel and negative for equilibrium fuel.

The overall effect is that voiding the coolant results in a ***positive*** reactivity, which is greatest with fresh fuel. The total reactivity change for **full core** voiding is typically in the range of 7 to 13 mk, depending on the degree of fuel burnup.

Voiding the coolant also reduces the amount of absorbing material in the reactor; for heavy water coolant, however, this decrease is very small provided the coolant isotopic is high. In practice, there is a lower limit on isotopic to prevent an excessively large reactivity change upon voiding. This lower limit is usually in the range of 97 to 97.5%.

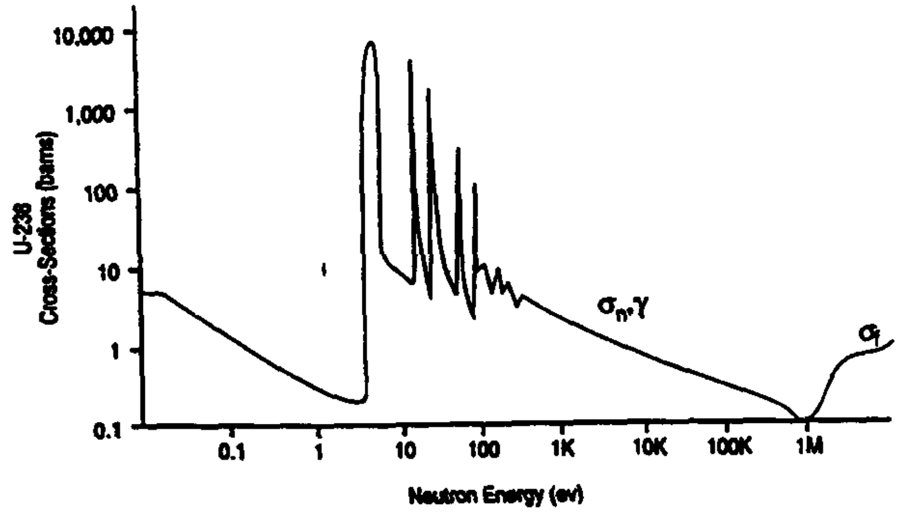


Figure 12.13: Variation of capture and fission cross-sections of U-238 with neutron energy

Power surges due to voiding

Excessive positive or negative void reactivity changes should be avoided if possible. An excessively large positive reactivity will cause large power surges during the void formation which are likely to cause severe damage to the reactor if the protective system does not respond quickly enough.

On the other hand, excessive negative void reactivity changes cause a rapid decrease in power when the void is formed, which the regulating system attempts to compensate by increasing the reactivity. Then, when the void collapses, a power surge again results.

ASSIGNMENT

1. Explain why the fuel temperature coefficient of reactivity is more important than either the coolant or moderator coefficient with respect to limiting power transients. (Give two reasons).

2. Define the power coefficient of a reactor.

3. Explain why the fuel temperature coefficient is larger in magnitude for fresh fuel than for equilibrium fuel.

4. Cite one practical use of the moderator temperature coefficient.

5. Explain why void formation in the coolant of a CANDU reactor leads to an increase in reactivity.

6. Considering only the effect on the reactivity change due to void formation, explain why it is undesirable to add soluble poison to the coolant.

7. Why is it undesirable to have excessive positive or negative changes of reactivity due to void formation in a reactor?

8. Briefly discuss the advantages and disadvantages of having a negative fuel coefficient of reactivity in operating CANDU reactors.