

21 Reactivity Effects of Temperature Changes

21.1 The NRX Experiment and Negative Feedback

In 1949, the NRX reactor at the Chalk River Nuclear Laboratory was allowed to "run away" in a controlled test. NRX was a heavy water moderated experimental reactor that used control rods for reactor regulation. The heavy water level was set 3 cm above the height at which the reactor would be critical at low power with the rods withdrawn. The reactor power was allowed to increase "unchecked". (Had there been any surprises it could have been quickly shut down.) The manner in which power changed is not what you might expect based on what you learned previously (See Figure 21.1).

Initially the power increased, but it did not increase indefinitely as you might have expected. As the fuel temperature increased, reactivity decreased and this caused the rate of power rise to slow. Later the reactivity decreased even more as the heavy water got warmer. The total decrease in reactivity was enough, in this demonstration, to make the reactor sub-critical. Consequently, power reached a maximum and began to decrease.

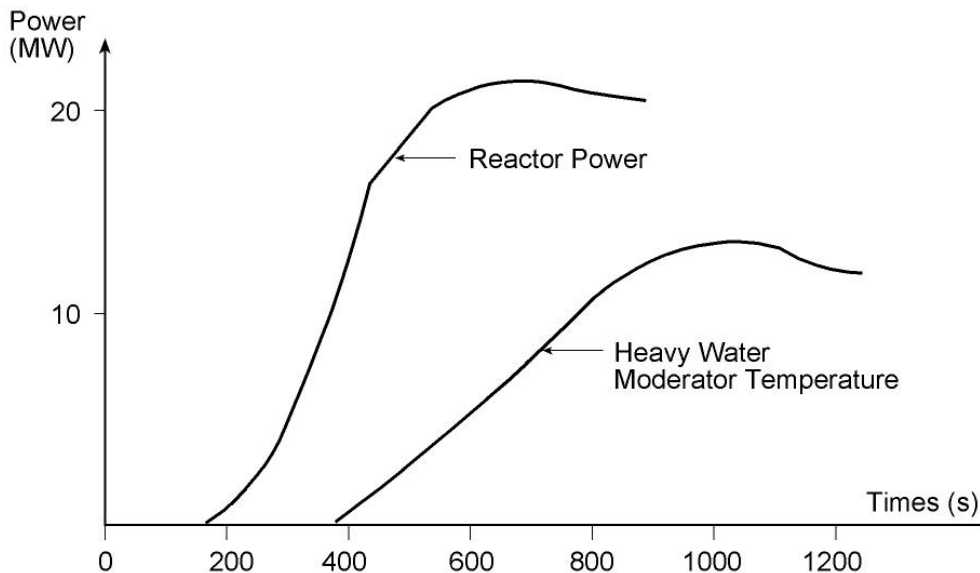


Figure 21.1

The NRX Experiment

The test demonstrated that for small, positive reactivity insertions the NRX reactor was self-regulating. The temperature increases associated with the power increase reduced reactivity, preventing the power from increasing indefinitely.

The power would have continued to rise had the initial reactivity insertion been larger. The point of this example is not to demonstrate that reactor power cannot continuously increase (it well might), but to show that there is a loss in reactivity due to the increase in the temperatures of fuel and heavy water.

Commercial CANDU reactors respond similarly and normal reactor power regulation includes this effect. When a large power increase is required, the regulating system automatically ramps the power in a sequence of small steps. The combination of repeated small reactivity additions and reactivity losses as power rises produces a smooth power increase with very little intervention of the control system needed to limit power rise.

Compare this with what you expect from previous modules, where Δk was assumed not to change. (This is how a reactor behaves when it is super-critical at low power, where the heating effects are very small.) Even a small initial Δk giving a long reactor period eventually leads to a rapid power increase. Power increases faster and faster as time goes on. In the power range that produces significant heat, too fast an increase can lead to equipment failure. The regulating system would need to initiate the power increase by adding a positive Δk and then continually reduce Δk , actively limiting the rate of increase.

The advantage of reactivity loss with power increase is not clear-cut if there is an accidental insertion of a larger amount of positive reactivity. The rate of power rise is a bit slower, which might help. If the accidental insertion is not too big, power might eventually stop rising, but not necessarily below 100%. On the other hand, these effects, if significant, are likely to delay initiation of an automatic trip.

21.2 Temperature Coefficients

The temperature coefficient of reactivity is the change in reactivity per unit temperature increase. It may be positive or negative. It was negative in the example above, because a temperature increase caused a reactivity loss. The units of temperature coefficient are $\text{mk}/^\circ\text{C}$.

Temperature changes occur more or less independently in the fuel, the heat transport system, and the moderator. There is a temperature coefficient of reactivity associated with each of these. The “self-regulating” characteristics illustrated above require the overall temperature coefficient of a reactor to be negative, but changes in fuel temperature are the most important in determining the overall coefficient.

The change in reactivity caused by coolant temperature changes is normally very small (and difficult to explain). Moderator temperature changes cause significant reactivity changes, but normal control keeps the moderator temperature constant. Furthermore, moderator heating and cooling are relatively slow (because of the large amount of D_2O), so the effect is not as immediate as the fuel reactivity effect. This course examines only the effects caused by the temperature changes in the fuel.

21.2.1 Fuel Temperature Coefficient of Reactivity

There are two main contributions to the fuel temperature coefficient:

1. Increasing fuel temperature increases resonance capture in U-238.
2. The ratio of fission to absorption in the fuel changes with fuel temperature. (The direction and size of the change depend on whether the fuel is fresh, or there is equilibrium fuelling).

We will look at both effects in turn.

Increased Resonance Absorption

The change in resonance absorption with temperature is always the most important fuel temperature effect.

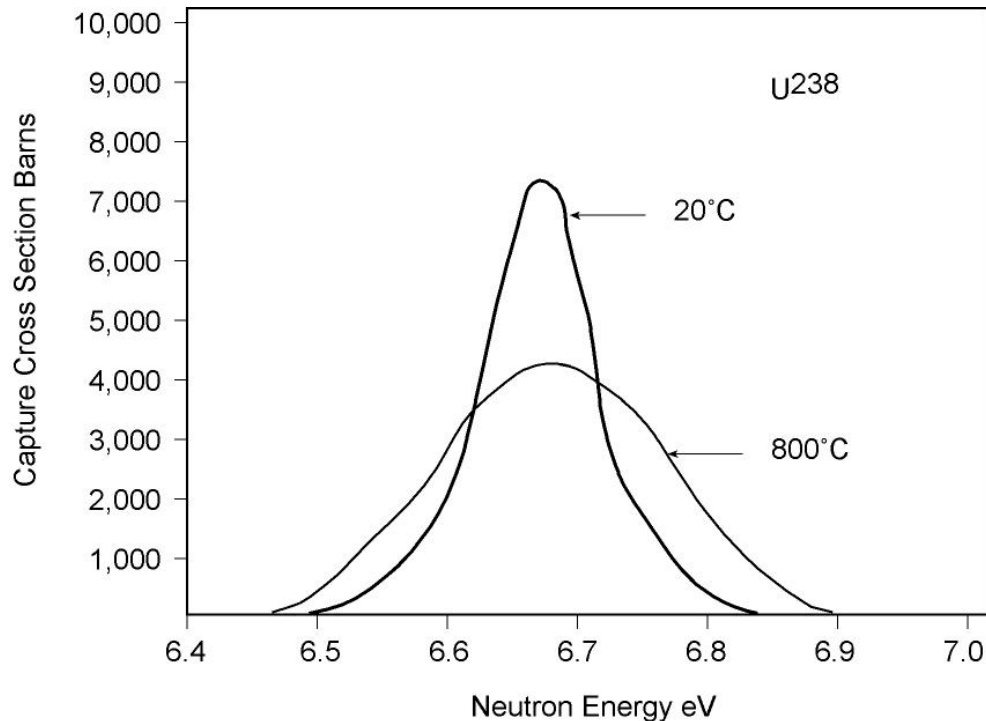


Figure 21.2
Resonance Broadening

Resonance capture accounts for about 10% of neutron loss in a CANDU core. The absorption of resonance energy neutrons in U-238 increases strongly as the fuel temperature increases.

The reason for increased resonance capture is as follows. The width and height of the resonance peaks in the U-238 cross-section depend on the temperature of the U-238. Figure 21.2 shows one particular resonance peak at 20°C and another at 800°C. At the higher temperature, (typical of the effective fuel temperature at high power) the peak is lower, but still high enough to capture almost any neutron in this energy range. At the same time, the resonance spreads over a wider range of neutron energies, exposing more neutrons to capture. Fewer neutrons entering the fuel while thermalizing are able to escape.

Ratio of Fissions to Absorptions

The variation of neutron cross-section with neutron energy has already been introduced. Temperature changes in the thermal neutrons' environment, which includes the hot fuel, are reflected in the thermal neutron energy. Cross-sections for thermal neutrons (apparent target size) get smaller at higher neutron speed, but not all cross sections change in the same way. You should expect the ratio of fission to absorption in the fuel to change with neutron temperature. For fresh fuel, where U-235 is the only fissile nuclide, this ratio goes down as thermal neutrons speed up. For equilibrium fuel, with a significant quantity of Pu-239, the ratio increases.

$$\left(\frac{\sigma_f^{\text{fuel}}}{\sigma_a^{\text{fuel}}} \right)$$

For fresh fuel, as the thermal neutrons get “hotter”, fewer of the neutrons absorbed in the fuel cause fission of the U-235. The opposite effect is observed for fuel with plutonium in it. A non-technical summary of this “hot neutron effect” may help you remember it. U-235 prefers cold neutrons; Pu-239 strongly prefers hot neutrons. Thus, for fresh fuel, increasing thermal neutron temperature decreases reactivity. For equilibrium fuel, reactivity increases with increasing thermal neutron temperature.

Combined Effect

As power rises, the fuel heats up. This broadens the U-238 resonances and heats up the thermal neutrons. The overall change in reactivity is a

combination of both effects. The resonance absorption effect is always larger than the “hot neutron effect”.

For fresh fuel, the fuel temperature coefficient is obviously negative, since both effects are negative. A typical value is $-0.013 \text{ mk}/^\circ\text{C}$. For equilibrium fuel, the strong plutonium effect partly offsets increased resonance capture, reducing the magnitude of the fuel temperature coefficient to about $-0.004 \text{ mk}/^\circ\text{C}$.

21.2.2 Power Coefficient

Operationally the reactor power is measured and fuel temperature is not. In studying the behaviour of the reactor as power changes, it is handy to define the power coefficient. The power coefficient is the change in reactivity caused by temperature effects when power increases from zero power hot to full power.

A typical value for CANDU reactors is $\approx -5 \text{ mk}$, a decrease in reactivity. The exact value depends on the reactor design and fuel condition. For Bruce B the values are about -9 mk for fresh fuel and -3.5 mk for equilibrium fuel. The reactivity change is almost uniform in the high power range. A power coefficient of -3.5 mk suggests that a 10% increase in power (for example, ramping power from 80% to 90%) results in a loss of about 0.35 mk , equivalent to about 5% change in zone level.

21.2.3 Void Reactivity

If boiling occurs in a coolant channel, steam gradually displaces coolant. The name of this effect is voiding. Partial or total void in a channel affects resonance capture, parasitic absorption, fast fission, and leakage. We leave the explanation of these effects to a more advanced course.

The void reactivity is the change in reactivity for 100% voiding of all coolant channels. It is positive in CANDU reactors. The actual value varies from reactor to reactor but is about $+10 \text{ mk}$ for the Bruce reactors.

$+10 \text{ mk}$ is a very large positive reactivity, able to cause an unacceptably fast power rise. However, it is not ordinarily possible for all the coolant to flash rapidly to steam, even on a large pipe break. The safety systems are designed to detect and stop the power rise long before the $+10 \text{ mk}$ of reactivity is inserted. There are two independent, fast, automatic, safety shutdown systems to make sure a shutdown occurs.

21.3 Summary of Key Ideas

- CANDU fuel has a negative temperature coefficient. As the temperature of the fuel rises, negative reactivity is added to the core.
- The fuel temperature coefficient is comprised primarily from the broadening of U-238 resonance absorption peaks and the change in cross sections of nuclides in the fuel.
- The power coefficient is the total change in reactivity as the reactor power is raised for zero power hot to full power. In a CANDU, this coefficient is negative.
- The void coefficient of reactivity is the reactivity change in the core if the heat transport system voids. In a CANDU reactor this reactivity insertion is positive.

21.4 Assignment

1. Define:
 - a) temperature coefficient,
 - b) power coefficient,
 - c) void reactivity.
2. Discuss the reasons why the fuel temperature coefficient is negative and why the magnitude is lower for equilibrium fuel than it is for fresh fuel.
3. Why is a negative temperature coefficient desirable?

