Nuclear Theory - Course 227

REACTIVITY EFFECTS DUE TO TEMPERATURE CHANGES

In the lesson on reactor kinetics we ignored any variations in reactivity due to changes in power. As we saw in the previous lesson there are marked changes in reactivity due to xenon; occurring over a period of minutes to hours after an overall power change. Changes in reactor power causes changes in the temperature of the fuel, moderator, and coolant. These also have an effect on reactivity which is more rapid than xenon effects.

The NRX Experiment

In 1949, the NRX reactor at AECL, Chalk River, was allowed to "run away". NRX is a heavy water moderated reactor which uses 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 The heavy water level was set 3 cm above the height at which the reactor would be critical at low power with the rods withdrawn.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, and the manner in which it increased is rather unexpected (see Figure 1).

The power initially increased exponentially with a period of 33 seconds ($T = 33$ s, $\Delta k = +1.6$ mk). However, it did not increase indefinitely as you might have expected. As the temperature of the fuel rods increased, the reactivity decreased and this caused the rate of power increase to slow down. Later the reactivity decreased at a faster rate as the heavy water got 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 is self-regulating with temperature increases preventing the power from continuing to increase. Of course, in this experiment the initial excess reactivity was quite small; if more reactivity had been inserted initially it is quite possible that the power would have continued to rise. The point of this example is not to demonstrate that reactor power would never increase continuously (it well might), but to show that there was a loss in reactivity due to the increase in the temperatures of fuel and heavy water.

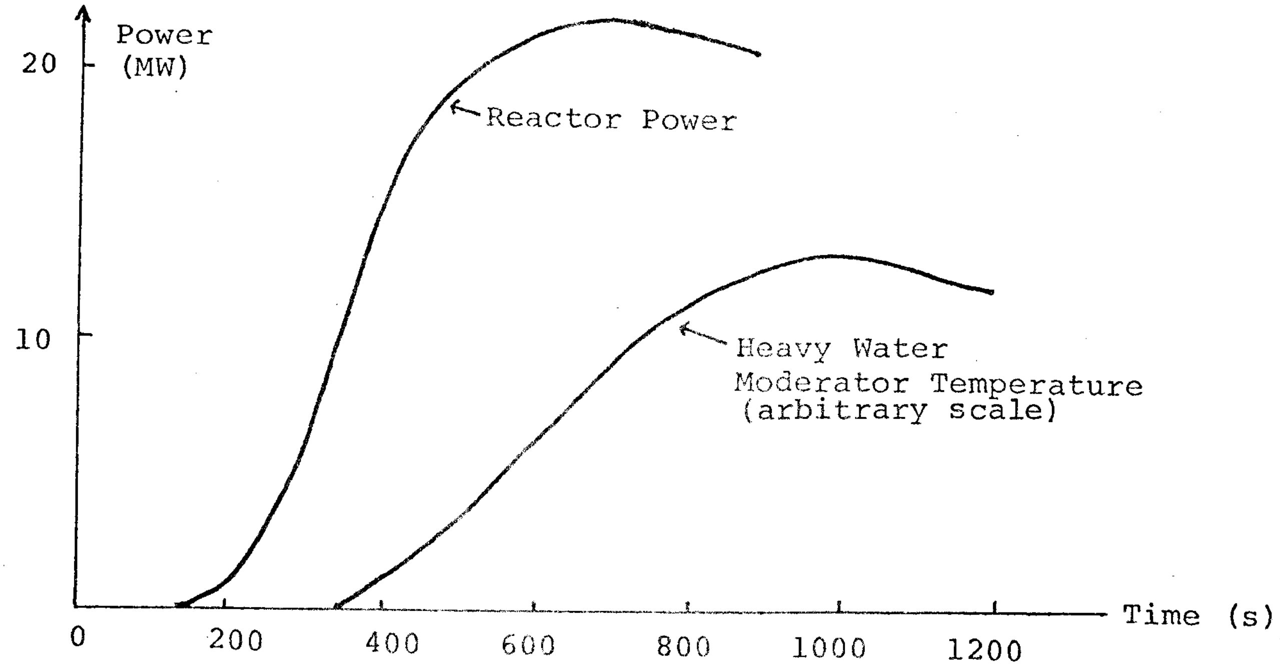

Fig. 1 The NRX Experiment

The *temperature coefficient of reactivity* is defined as the change in reactivity per unit increase in temperature. Its units are mk/°C.

The coefficient may be positive or negative. In the example just described it was negative, because an increase in temperature led to a loss or reactivity.

Temperature changes occur, more or less independently, in the fuel, the heat transport system and the moderator, and there will therefore be a temperature coefficient of reactivity associated with each of these. It is very desirable for the overall temperature coefficient of a reactor to be negative to provide the self-regulating feature illustrated by NRX.

In order to fully understand why changes in temperature cause changes in reactivity it is necessary to understand both the physical and nuclear properties which change with temperature.

(a) Thermal Expansion Effect

As the temperature of the coolant and/or moderator increases its density decreases. As a result neutrons travel further thus, they have an increased probability of escaping (Λ_f and Λ_{th} may both decrease). Also with fewer moderator molecules there is less absorption in the moderator and thermal utilization (f) increases.

(b) Direct Nuclear Effect

This is the effect commonly known as *Doppler Broadening*. We mentioned earlier in the course that resonance capture occurs in U-238 for certain neutron energies related to the target nucleus which was assumed to be at rest. The resonance is actually determined by the relative velocity of the neutrons and the target nuclei. When the fuel gets hot, the uranium atoms will vibrate more vigorously. A neutron which would have been outside the resonance peak if the uranium atoms had been at rest, may encounter an atom moving at the necessary speed to put their relative velocity in the resonance peak. Thus the neutron, which might have survived in cold fuel, is now captured in hot fuel, and this is reflected in a spreading of the resonance peak as shown in Figure 2. There will then be a decrease in the resonance escape probability p and in the reactivity due to this so-called Doppler Broadening of the resonance peak*.

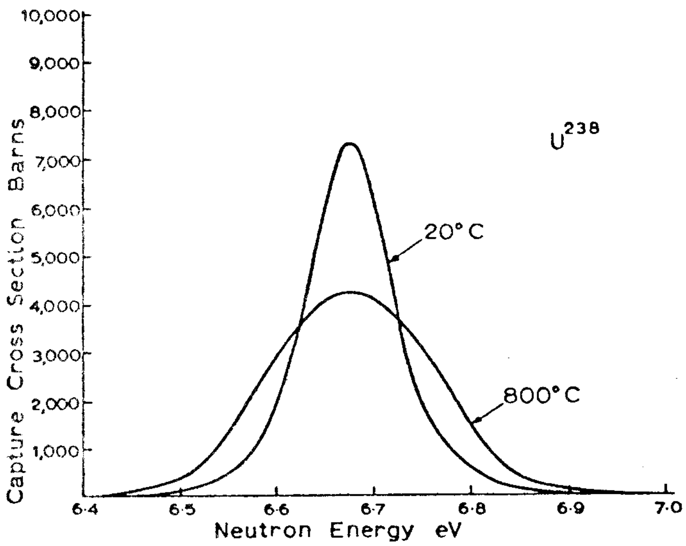

Fig. 2 Doppler Broadening

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*Without a rigorous mathematic treatment it may not be easy to convince you that although the area under the curve is the same, the absorption increases. A simple (but basically correct) approach is to say that although σ_a for hot fuel is only half of what it is for cold fuel, it is high enough to virtually guarantee absorption of any resonance energy neutrons entering the fuel. Only now the resonance energy range has been doubled.

(c) Indirect Nuclear Effect

A thermal neutron is one which is in thermal equilibrium with its surroundings. Clearly then any change in the temperature of the moderator, coolant, or fuel will affect the average thermal neutron energy. Thus neutron cross sections, being energy dependent, are affected. This may affect the thermal utilization (f) and the reproduction factor (η). Generally the changes in η which are most significant, are due to changes in the ratio of the fission cross section to the absorption cross section of the fissile material $\left(\sigma_f/\sigma_a\right)$.

Figure 3 shows the variation of η for U^{235} and Pu^{239}. Note in particular that around 0.3 eV, η for Pu^{239} starts to rise rapidly

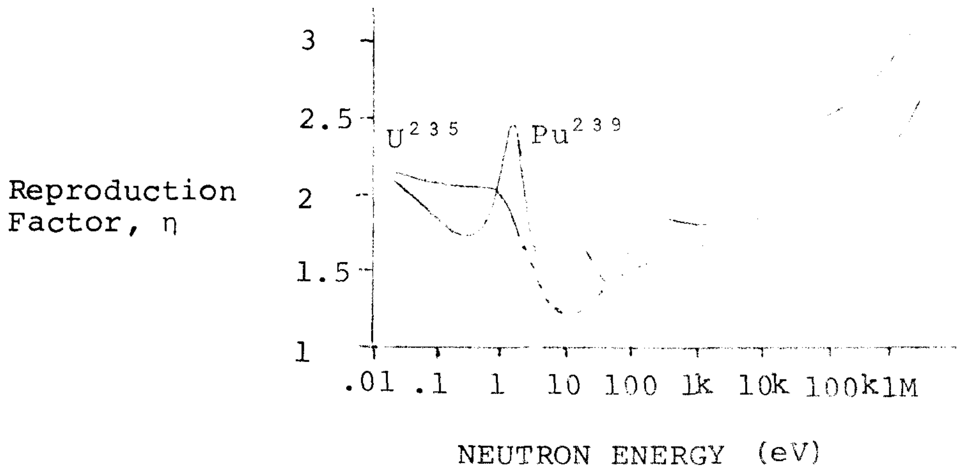


Figure 3

To evaluate the magnitude of the effects mathematically the Design Manuals evaluate the derivative of k with respect to temperature

$$\frac{dk}{dT}$$

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

$$\frac{1}{k}\frac{d}{dT}k = \frac{1}{\varepsilon}\frac{d\varepsilon}{dT} + \frac{1}{P}\frac{dP}{dT} + \frac{1}{\eta}\frac{d\eta}{dT} + \frac{1}{f}\frac{df}{dT} + \frac{1}{\Lambda_f}\frac{d}{dT}\Lambda_f + \frac{1}{\Lambda_t}\frac{d}{dT}\Lambda_t$$

The change in each of the factors is tabulated in Table I for both fresh and equilibrium fuel. We will now look at the temperature coefficients for the fuel, moderator and coolant.

Fuel Temperature Coefficient

There are two primary effects due to an increase in the fuel temperature:

1) Increased resonance absorption

2) An altered ratio of fission to absorptions in the fuel.

Let us look at a concrete example. Table I gives makeup of the fuel temperature coefficient for the Pickering units at nominal operating conditions.

From this table you can see that the predominant term is the resonance capture term. It is sufficiently large to ensure an overall negative fuel temperature reactivity effect at nominal operating conditions, and it therefore provides the self-regulating feature that is so desirable.

TABLE I

Fuel Temperature Coefficient For Pickering Units 1-4

(Nominal Operating Conditions. Units are μk/°C)

	Fresh Fuel	Equilibrium Fuel
$(1/\varepsilon)d\varepsilon/dT$	0	0
$(1/p)dp/dT$	-9.33	-9.29
$(1/f)df/dT$	-0.79	+0.34
$(1/\eta)d\eta/dT$	-4.04	+5.33
$(1/\Lambda_f)d\Lambda_f/dT$	0	0
$(1/\Lambda_t)d\Lambda_t/dT$	-0.83	-0.43
TOTAL	-14.99	-4.05

The resonance escape term $\left(\frac{1}{P}\ \frac{dP}{dT}\right)$ is negative because increasing the fuel temperature causes increased resonance capture due to doppler broadening. Fresh and equilibrium fuel values are the same because the amount of U^{238} in the reactor is essentially constant.

The reproduction factor term $\left(\frac{1}{\eta} \frac{d}{dT} \eta\right)$ is negative for fresh fuel because the fissile material is all U^{235} and η decrease with increasing temperature in the U^{235} for energies of interest (< 1 ev) as shown in Figure 3. For equilibrium fuel this term is positive due to the increased concentration of Pu^{239}. The increase in η with temperature for Pu^{239} overwhelms the negative effect of the uranium.

The behavior of the thermal utilization term is also due to the increased concentration of plutonium. (The plutonium increases at 80% of the uranium 235 depletion. Thus 0.8 x 741.6 = 593 b > 580 b the cross section for U235.)

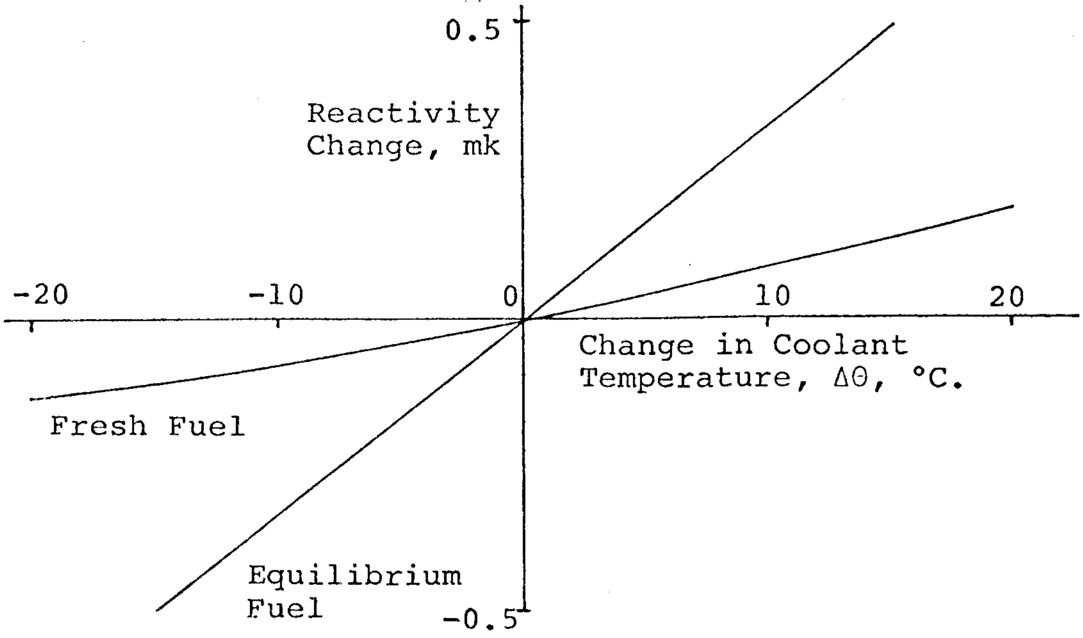
The change in thermal leakage is due to an increase in the distance a thermal neutron diffuses, which is brought about by an overall reduction in the thermal absorption cross section of the whole core.

Heat Transport Temperature Coefficient of Reactivity

The reactivity effect associated with a change in coolant temperature is rather more complicated in its make-up than the fuel temperature effect, and we won't discuss it in detail.

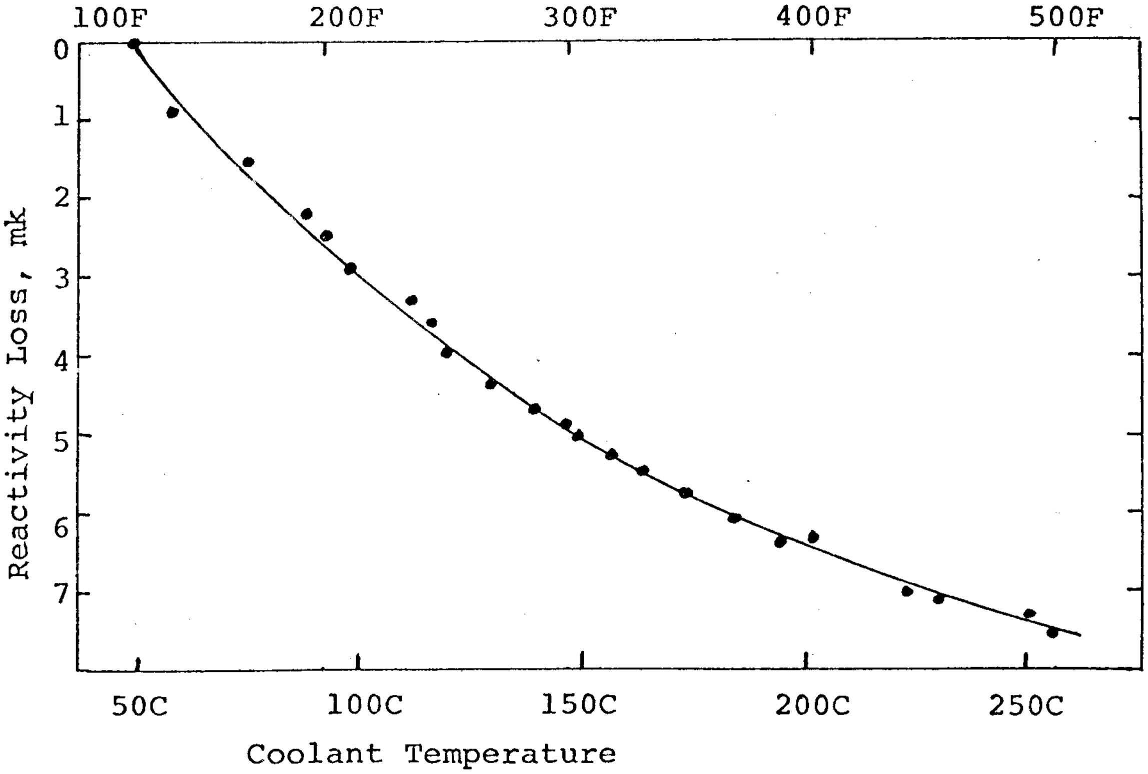
Figure 4 shows the overall coolant temperature coefficient of reactivity for the Pickering units as calculated from the design data. It is very difficult to determine it from measurements, because you can't change the coolant temperature without changing the fuel temperature. It is however positive.

Figure 5 shows the results of measurements made on Pickering Unit 3 when it contained fresh fuel. The heat transport system was heated by running the primary pumps while the reactor was held critical at 0.1% of full power. The measurements extended over a period of 13 hours so that one must assume that the fuel temperatures kept in step with the coolant temperatures. The measured changes in reactivity therefore reflected both the fuel and the heat transport coefficients of reactivity, and you can see that the negative effect of the former more than compensates for any positive effect of the latter. The reactivity change is seen to be -7 mk from cold shutdown to hot shutdown.



Calculated Change in Reactivity Versus Change in Coolant Temperature (Pickering Units 1-4)

Figure 4



Reactivity Loss Versus Coolant Temperature (Pickering Unit 3, Fresh Fuel)

Figure 5

Moderator Temperature Coefficient of Reactivity

As with the fuel temperature coefficient there are two effects; change in moderator density and increasing average thermal neutron energy. The temperature of the moderator affects the neutron energy much more than coolant or fuel does - it is the base temperature, so to speak. One would therefore expect the magnitude of the moderator coefficient to be greater than the other two, and this is in fact the case, as you can see from Table II which again gives the values applicable to Pickering.

TABLE II

Moderator Temperature Coefficient for Pickering Units 1 - 4

(In units of μk/°C, calculated for ΔT = -13°C)

	Fresh Fuel	Equilibrium Fuel
$(1/\varepsilon)d\varepsilon/dT$	0	0
$(1/p)dp/dT$	-24.0	-23.9
$(1/f)df/dT$	55.4	67.1
$(1/\eta)d\eta/dT$	-59.2	76.0
$(1/\Lambda_f)d\Lambda_f/dT$	-13.0	-13.0
$(1/\Lambda_t)d\Lambda_t/dT$	-28.7	-22.0
TOTAL	-69.5	+84.2

The change in moderator density is responsible for an increase in the distance a neutron travels in slowing down. This in turn leads to a decrease in the resonance escape probability, p, as well as in the fast non-leakage probability.

The distance a neutron diffuses also increase. It is not only affected by the change in moderator density, but also by the reduction in all the absorption cross sections with increasing thermal energy. Consequently, the change in thermal leakage is greater than that in fast leakage.

The great changes in the value of η from fresh to equilibrium fuel are due to the effects of the ratio of fission to absorption in Pu^{239} and U^{235} as previously stated.

The thermal utilization term is always positive due to a decrease in absorption by the moderator associated with a decrease in moderator density.

Practical Aspects

We have already mentioned that it is desirable for the temperature coefficients to be negative so that a self-regulating feature is provided. However, more must be considered than just the values of the three temperature coefficients. Two most important additional factors are; the size of the various temperature changes for a given power change, and the time period over which the changes occur.

Typically, in a change from hot shutdown, to 100% power, the average coolant temperature may increase by ≈ 20 - 40°C while the average fuel temperature will increase by 500 to 600°C and the moderator temperature will be maintained constant. Furthermore, the fuel temperature will change nearly instantaneously as the power changes while the coolant temperature change will lag the power change by a few seconds.

Thus, we achieve the desired self-regulation merely by having a negative fuel temperature coefficient of reactivity.

A negative temperature coefficient does, however, create some problems. In heating the fuel and coolant from a cold shutdown condition to a hot shutdown condition there is a net loss of reactivity worth which can be as much as 9 mk. Also, when power is increased there is a reactivity loss which must be compensated for. In Ontario Hydro, this is expressed in terms of the *power coefficient*, which is defined as the reactivity change in raising power from hot shutdown to 100% full power. It only includes the temperature coefficients of reactivity, and not any reactivity loss due to fission product formation. It is typically of the order of 5 or 6 mk for a heavy water reactor.

Effects Due to Void Formation

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

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

The liquid coolant may boil as a result of:

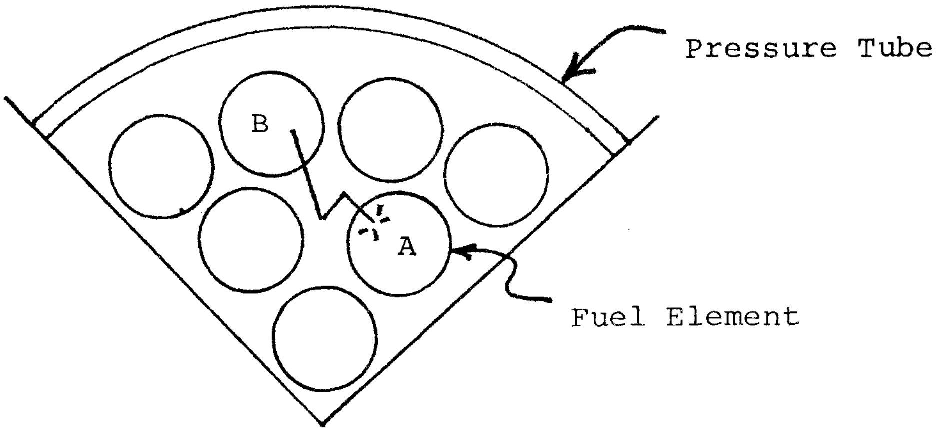
- rupture of the feeder pipe(s)
- failure of the primary pump(s)
- large power excursions
- channel blockage.

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

The severity of the above emergency conditions depends primarily on the rate of reactivity addition, although the total reactivity addition may be of equal importance. For a light water cooled reactor, such as Gentilly, loss of coolant results in a very large change in reactivity. For example, it is estimated that for Gentilly, operating with fresh fuel, the reactivity change for a loss of coolant in half the core can be as high as 37 mk, depending on the operating conditions at the time. This colossal change is of course primarily due to the increase in the thermal utilization, f, caused by the loss of H_2O absorber.

For D_2O cooled reactors, the effects are nowhere near as drastic, although they are still very important.

Voiding of fuel channel causes a decrease in the moderation of neutrons in the immediate neighborhood of the fuel elements. Looking at figure 6 (a quadrant of a fuel bundle) you can see that a neutron born in one fuel element (eg, element 'A') normally passes through some coolant before reaching the next fuel element (element 'B') with the coolant providing a little moderation. With the channel voided there is no moderation hence, higher energy neutrons are interacting with the fuel in element B.



Quadrant of a Fuel Bundle

Figure 6

This has two effects which can be seen by looking at the radiative capture and fission cross sections of U^{238} shown in Figure 7

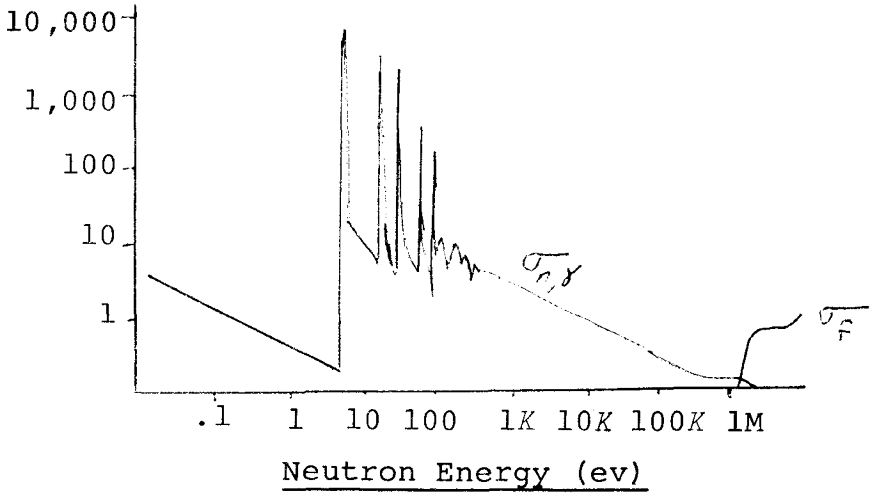


Figure 7

(a) An increase in the fast fission factor (ε) since σ_f increases with increasing energy.

(b) An increase in the resonance escape probability (p) since $\sigma_{\eta,\gamma}$ decreases with increasing neutron energy.

Both of these give rise to a positive void coefficient.

Voiding of the coolant also reduces the amount of absorbing material in the reactor, however, for heavy water coolant, this decrease is very small provided the coolant isotopic is high. In practice there is a lower limit on coolant isotopic to prevent an exessively large void coefficient. This lower limit is usually defined in Station Operating Policy and Principles. (eg, 97% at Bruce NGS 'A').

Excessive positive or negative void coefficients are to be avoided if possible. An excessively large positive coefficient 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 enough.

Excessive negative coefficients, on the other hand, cause a rapid decrease in power when the void is formed, which is then corrected for by the regulating system. Then, when the void fills, a power surge again results.

ASSIGNMENT

1. Explain why the fuel temperature coefficient of reactivity is more important than either the coolant or moderator temperature coefficient of reactivity. (Two reasons.)

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

3. Cite an example of when the moderator temperature coefficient of reactivity may be useful.

4. Considering only the effect on the void coefficient, explain why it is undesirable to add soluble poison to the coolant.

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