Nuclear Theory - Course 127

EFFECTS DUE TO TEMPERATURE CHANGES AND VOID FORMATION

When a reactor is operated at power, fission products and xenon poison build up and fissile material, in the form of U-235 and plutonium is consumed. These effects will be considered later. In addition to such effects, operation at power also causes increases in the temperatures of the fuel, heat transport fluid and moderator. It is the changes in reactivity, resulting from these temperature changes, that will be considered in this lesson.

Formation of voids in the heat transport fluid or moderator, due to boiling or accidental loss of fluid, is closely connected with temperature changes. Therefore, void formation and its effect on reactivity will also be discussed.

Effects Due to Temperature Change

In 1949, the NRX reactor at AECL was allowed to "run away". NRX is a heavy water moderated reactor which also uses control rods. The heavy water level was set 3 cm above the low power critical height and the control rods withdrawn. The reactor power was allowed to increase unchecked and the manner in which the power increased is rather unexpected. Fig. 1 shows the manner in which reactor power increased and the way in which the heavy water temperature changed.

The power initially increased exponentially as would be expected with a period of 33 sec. However, it does not continue to increase indefinitely as would have been expected. The reactivity started to decrease, because the temperature of the fuel rods increased. This causes the power increase to slow down. Later the reactivity decreased at a faster rate because of the increase in the heavy water temperature. The decrease in reactivity was sufficient to cause the reactor reactivity to become negative, with the result that the power reached a maximum value and then started to decrease. Thus the reactor is self-regulating with the temperature increases, preventing the power from continuing to rise, as it would otherwise have done. Of course, the initial period of 33 sec shows that the excess reactivity was only 3 mk in the first place. Had more reactivity than this been added, ie, had the moderator level been higher, it is quite possible that the power would have continued to rise. This example is not being used to demonstrate that reactor power would never increase continuously, but to show that there was a loss of reactivity due to

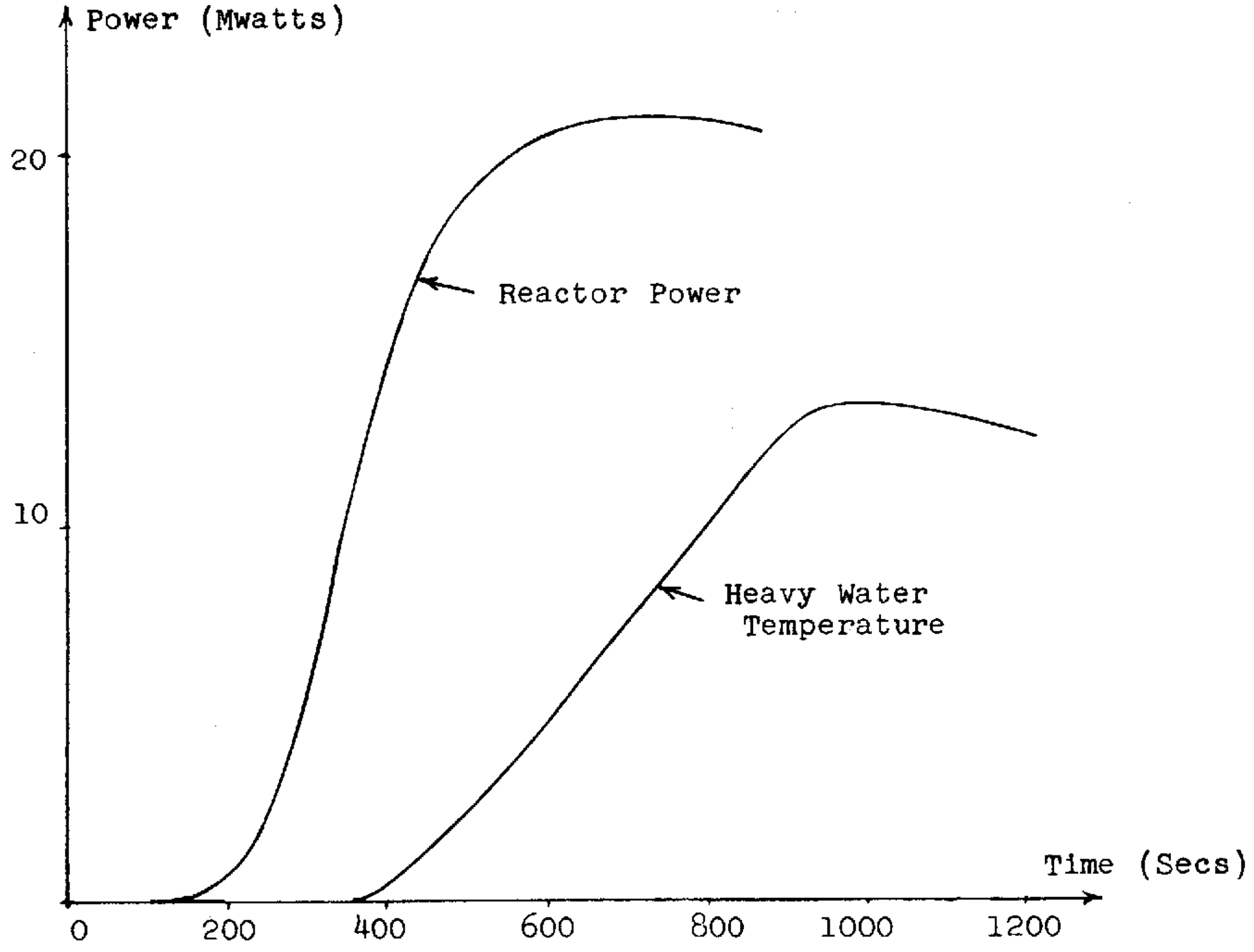

Fig. 1

the increase in the temperatures of fuel and heavy water. However much reactivity was initially added and however fast the initial power rise, the increase in power would slow down somewhat when the temperatures start to increase. This rapid loss in reactivity is sometimes known as PROMPT POISON.

The amount of prompt poison is often measured in terms of the reactor POWER COEFFICIENT. This is defined as the change in reactivity per unit increase in power.

When the reactivity decreases with increase of temperature, the reactor is said to have a NEGATIVE TEMPERATURE COEFFICIENT.

If the reactivity had increased with increase of temperature, then the temperature coefficient would be positive.

The Temperature Coefficient of Reactivity may be defined as the milli-k change in reactivity per 1°F increase in temperature.

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

Changes in reactivity with change in temperature occur for a number of reasons which are discussed below.

Factors Causing Reactivity Changes With Temperature

Factors which cause changes in reactivity when the temperature increases may be divided into three main categories as follows:

(a) Mechanical changes which may in turn be due to:

   (1) decrease in density of the moderator and heat transport fluid, allowing the neutrons to move further. The neutrons are not slowed down so rapidly nor are they captured so quickly, ie, L and L_s increase and the chances of the neutrons escaping are higher. $L\uparrow, L_s\uparrow$

   (2) the fuel elements expanding with temperature, and this reduces the amount of heat transport fluid surrounding the fuel. If the heat transport fluid is light water this will result in a decrease in neutron capture and a consequent increase in reactivity. With heavy water in the heat transport system the change in reactivity will be positive if the reactor is overmoderated, ie, if the moderator to fuel ratio is greater than that required for maximum reactivity. If the reactor is undermoderated there will be a decrease in reactivity. $k\uparrow$

(b) Direct Nuclear Effects - This is the effect commonly known as DOPPLER BROADENING. It is usually stated that resonance capture occurs in U-238 for certain neutron energies but this implies that the target nucleus is at rest. The resonance is actually determined by the relative velocity of the neutrons and the target atoms. If the uranium is hot the atoms are vibrating, and a neutron which would be outside the resonance peak, had the uranium atoms been at rest, may encounter an atom which is moving at the necessary speed to put their relative velocity in the peak. Thus the neutron, which might have escaped in cold fuel, is captured and there is a decrease in the resonance escape probability and in the value of k_∞ due to this so-called Doppler Broadening of the resonance. $p\downarrow$ $k_\infty\downarrow$

(c) Indirect nuclear effects which may be due to:

(1) changes in the so-called NEUTRON TEMPERATURE. The thermal neutrons in a reactor have a distribution of energies approximating to the Maxwellian distribution of energies of molecules, with a characteristic temperature somewhat above the reactor temperature. This effective neutron temperature has been estimated to be equal to the moderator temperature plus $\frac{1}{4}$ of the temperature difference between moderator and coolant. Thus any increase in temperature of fuel, heat transport fluid or moderator will cause an increase in the neutron temperatures and an increase in the energies of thermal neutrons entering the fuel. In heavy water the main result is to reduce the absorption and thus increase k. In the fuel the ratio of absorption to fission changes causing a decrease in η for uranium and an increase in η for plutonium.

$T_m + \frac{1}{4}(T_m - T_c)$

$k\uparrow$

U↓

η for Pu↑

(2) changes due to plutonium buildup - Pu-239 has a resonance at 0.3 ev, so that the absorption in Pu-239 is increased relative to the other components as the fuel is irradiated. This produces a positive change in reactivity. Hence, in a reactor which may have a negative temperature coefficient with fresh fuel, the temperature coefficient will increase and may become zero or positive as the irradiation of the fuel increases, eg, the moderator temperature coefficient in NPD was estimated to be -0.067 mk per ^{o}F for fresh fuel and only +0.013 mk per ^{o}F for fully irradiated fuel.

It was mentioned earlier that reactivity changes could occur due to temperature changes in fuel, heat transport fluid or moderator and that there would be a temperature coefficient of reactivity associated with each component. These will now be discussed further.

Fuel Temperature Coefficient of Reactivity

The reactivity changes due to increased fuel temperatures are mainly due to two of the effects discussed above, namely:

↓fresh fuel
η ↑old fuel

(a) Increase in the effective temperature of the thermal neutrons in the fuel causing a decrease in η for fresh fuel and an increase in η for fully irradiated fuel.

$p\downarrow$

(b) An increase in resonance capture, with a resulting decrease in p due to Doppler Broadening.

In a reactor using the same type of fuel throughout, the fuel temperature coefficient would be expressed as the milli-k change in reactivity per ^{o}C (or ^{o}F). Thus, the expected values, due to each of the above effects, for equilibrium fuel in Douglas Point are as follows:

Neutron temperature	+0.0036 mk/°C
Doppler Effect	-0.014 mk/°C
Total fuel temperature coefficient	-0.0104 mk/°C

In a reactor such as NPD, where 7 and 19 element fuel is used, the effects differ for the two types of fuel element. It is, therefore, more convenient to express the fuel temperature coefficient, for the reactor as a whole, as the change in reactivity per 1% change in power. Since changes in power are reflected in changes in the average fuel temperature, T_f, and in the average heat transport temperature T_c, it is convenient to express the coefficient in:

$$mk/\%\ \Delta(T_f - T_c)$$

fuel PHT

ie, as the change in reactivity per 1% change in $(T_f - T_c)$.

The values in NPD for fresh fuel and fuel irradiated to 7200 Mwd/tonne U are as follows:

	Fresh Fuel	Irradiated Fuel	
Neutron temperature	-0.0121	+0.0085	$mk/\%\ \Delta(T_f - T_c)$
Doppler effect	-0.0272	-0.0272	$mk/\%\ \Delta(T_f - T_c)$
Total	-0.0393	-0.0187	$mk/\%\ \Delta(T_f - T_c)$

This table also shows the change that occurs in the neutron temperature effect, and consequently on the total fuel temperature coefficient, because of the plutonium buildup in the irradiated fuel.

When the fuel temperature coefficient is negative excess reactivity must be provided in the reactor to counteract the decrease in reactivity that occurs as the fuel heats up when reactor power is increased. Such a requirement may determine whether or not full power can be achieved under certain circumstances, particularly following a reactor trip. The buildup of xenon, following a reactor trip, limits the time during which the reactor can return to critical, as indicated in a later lesson. If criticality is achieved towards the end of this time limit and the fuel, in the meantime, has cooled down, there is insufficient excess reactivity left to allow for the decrease that occurs as the fuel heats up. Consequently the fuel temperature cannot be allowed to increase and the power cannot be raised. Since the xenon buildup cannot be removed until about 70% of full power is achieved, the xenon continues to build up and the reactor becomes subcritical.

Heat Transport Temperature Coefficient of Reactivity

An increase in the temperature of the heat transport system will result in a change of reactivity because:

(a) the temperature increase again causes an increase in neutron energy with the same results as with the fuel temperature coefficient above.

$f\uparrow$ $\epsilon\uparrow$ $p\downarrow$

(b) a reduction in density causing an increase in f and ϵ and decrease in p, the resonance escape probability.

The overall heat transport temperature coefficient is usually negative with fresh fuel but becomes less negative as plutonium builds up. Thus, in NPD the measured value of this coefficient with fresh fuel was -0.020 mk/°F whereas the present value with a close-to-equilibrium core is -0.003 mk/°F. The expected value with the Douglas Point equilibrium fuel is +0.023 mk/°C or about +0.013 mk/°F.

The negative value for this coefficient compounds the problem of returning to high power following a reactor trip. It is important that, should such a trip occur, the heat transport temperature be kept as high as possible until the reactor is back at high power. This in turn may require isolation of the steam generator from the turbine so that heat from the heat transport system is not being used to produce steam for the turbine.

If the algebraic sum of the fuel and heat transport temperature coefficients is positive, the reactivity decreases as reactor power decreases and the above problem no longer exists. However, such a system is less stable since a transient increase in power leads to a rise in temperature which results in an increase in reactivity which tends to raise the power further.

Moderator Temperature Coefficient of Reactivity

Changes in reactivity with increase in moderator temperature are due to:

(a) increase in the effective neutron temperature with the same results as with the fuel temperature coefficient above.

$L^2\uparrow$ $L_s^2\uparrow$ $p\downarrow$ $f\uparrow$

(b) decrease in moderator density with resulting increase in L^2 and L_s^2 and hence in neutron leakage. There is also a consequent decrease in p and an increase in f.

With new fuel, the moderator temperature coefficient is negative. As plutonium builds up it becomes less negative and may even become slightly positive because the increase in neutron energy increases fission capture in plutonium, whereas it decreases them in U-235.

The measured value in NPD with fresh fuel was -0.04 mk/°F and the manner in which this value was expected to change with fuel burnup is as shown in Fig. 2.

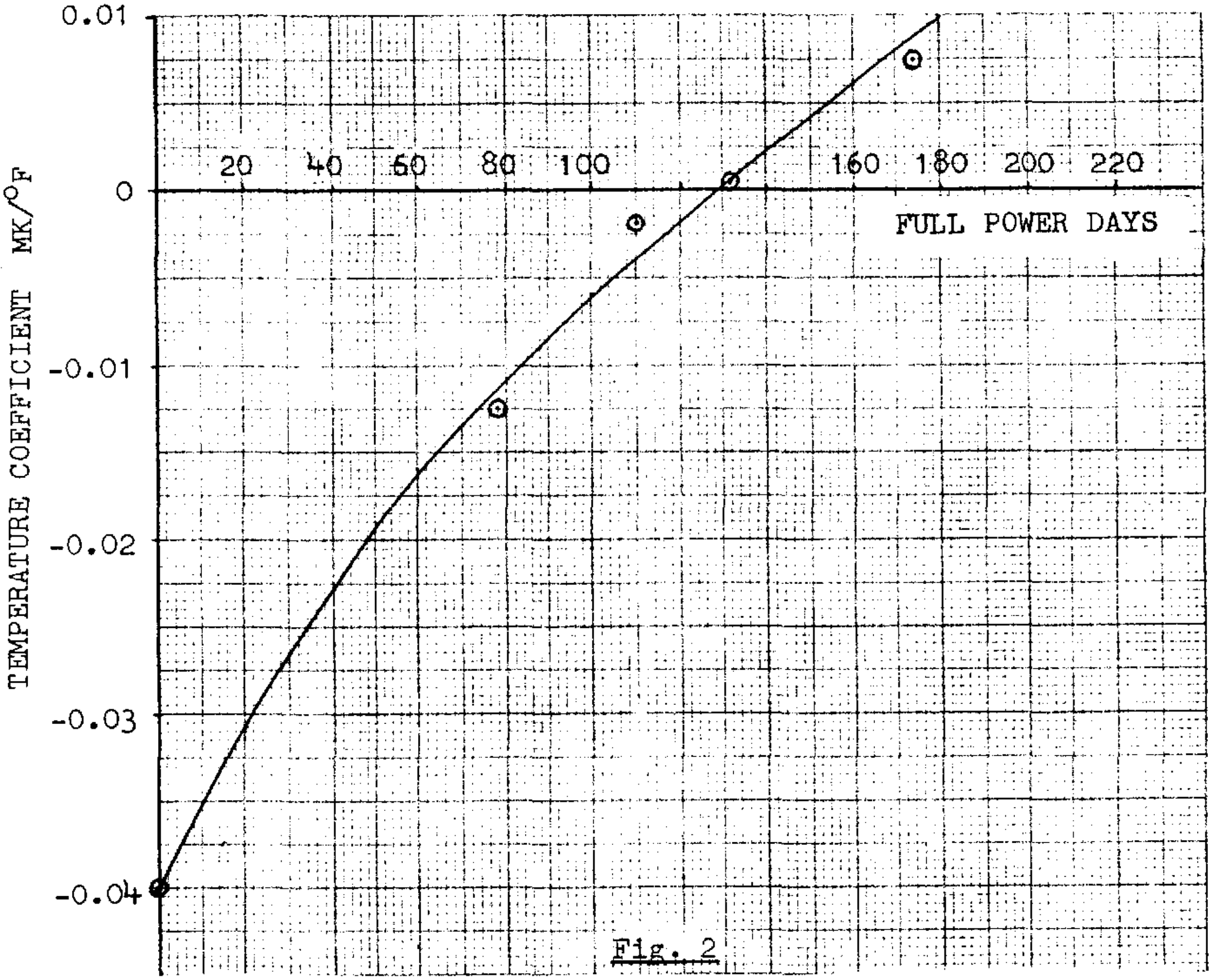

Fig. 2

After 300 to 400 full power days of operation the measured walue was +0.006 mk/°F. There are indications since then that the value has decreased back to zero but, nevertheless, it has become less negative as plutonium has been built up in the fuel.

A negative moderator temperature coefficient would allow some additional reactivity to be obtained, to help counteract a xenon transient following a reactor trip, by cooling the moderator.

Effects Due to Void Formation

Voids may be formed if either the moderator or heat transport system boils. This could be caused by an increase in heat generation, a decrease in cooling flow or a reduction in pressure due to a failure in the system. Generally, if a reactor is overmoderated, ie, with moderator/fuel ratio in excess of that required to just thermalize the neutrons, then a void formed in the moderator or in heavy water heat transport fluid, will cause an increase in reactivity. When the reactor is not overmoderated, then an increase in reactivity can still result. The size of the void and its location are important in deciding whether an increase or decrease in reactivity results from the formation of the void.

The void coefficient of reactivity is defined as the change in reactivity per 1% change in water volume.

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 rapidly 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.

Formation of voids in the heat transport system is of more concern than if they are formed in the moderator system. The heat transport system is pressurized to avoid boiling. However, an increase in fuel channel temperature, due to a power increase or decreased coolant flow can cause boiling. The resulting void could cause a large increase in reactivity, followed by a further increase in power, just when it was not wanted. A break in the heat transport system could cause loss of fluid with the same results due to drop in system pressure.

ASSIGNMENT

1. (a) What is meant by the statement that a reactor has an overall negative temperature coefficient?

   (b) Why is it desirable that a reactor have a negative, rather than a positive temperature coefficient?

2. Define temperature coefficient of reactivity.

3. (a) What factors cause the reactivity to change when the fuel temperature increases and what sort of changes does each factor cause?

   (b) What limitations might a negative fuel temperature coefficient impose on reactor operation?

4. What factors cause changes in reactivity when the heat transport temperature increases?

5. (a) What factors cause changes in reactivity when the moderator temperature increases?

   (b) Why does the moderator temperature coefficient become more positive as the fuel burnup increases?

6. (a) Define the void coefficient of reactivity.

   (b) Why is it undesirable to have excessive positive or negative void coefficients? power surges.

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Overmoderated - $\frac{\text{Mod}}{\text{Fuel}}$ ratio $\overset{\text{then}}{>}$ that needed to just thermalize the reactors.