Module 11

Fission Product Poisoning

July, 1997 (R-1)
I:\AUTHTRNG\BRUCE B\Initial Training\Science Fundamentals\22106 Nuclear Theory\Masters\Manual\22106-TM-11-R1.doc

11.1 MODULE OVERVIEW

Xenon-135

While most fission products build up slowly with fuel exposure, two of them, xenon-135 and samarium-149, are of particular operational importance. They have very large absorption cross-sections and they produce major changes in reactivity on a relatively short time scale.

We start by considering the mechanisms for creation and destruction of xenon and its precursor, iodine-135. This allows us to derive expressions for the equilibrium concentrations of I-135 and Xe-135. It also enables us to analyze the sequence of events following a ***shutdown*** after prolonged operation at power, and to understand why this leads to a rapid ***increase*** in Xe-135 concentration. This is important because it can result in a delay in restarting the reactor unless the control system can add large amounts of positive reactivity very quickly.

Xenon oscillations

Another important consequence of the presence of Xe-135 in a CANDU reactor is that it leads to the possibility of ***xenon oscillations***. These can cause reactor power to rise and fall with a period of 15-30 hours, with the possibility of over-rating the fuel. We will study the process by which xenon oscillations can occur, and see why they necessitate continuous flux monitoring at a number of points in the reactor.

Samarium-149

Finally, we will look at the effects of Sm-149. Although it does not create as dramatic an effect as Xe-135, it does contribute a significant reactivity at equilibrium, building up to a considerably larger load after shutdown. Unlike the xenon reactivity, this does not subsequently disappear, owing to the fact that Sm-149 is a stable isotope.

11.2 MODULE OBJECTIVES

After studying this module, you should be able to:

i) Explain how I-135 and Xe-135 are produced, and how they are lost from the reactor.

ii) Write the equations for the rates of change of the concentrations of I-135 and Xe-135, defining each term.

iii) State the magnitude of each production and loss term for Xe-135 at equilibrium in a typical CANDU reactor.

iv) Define xenon load and iodine load.

v) Sketch and explain the behavior of Xe-135 after a trip from full power.

vi) Explain what is meant by xenon simulation.

vii) Explain what a xenon oscillation is and how one starts.

viii) Sketch the behavior of Sm-149 after shutdown.

ix) Explain why Sm-149 growth after shutdown is not a problem.

11.3 XENON REACTIVITY BUILDUP

All fission products can be classified as reactor poisons because they absorb neutrons to some extent. Most simply build up slowly as the fuel burns up and are accounted for as a long-term reactivity effect (as we noted in Section 7.4.3). However, two fission products, Xe-135 and Sm-149, are themselves significant due to their large absorption cross-section and high production as fission products or fission- product daughters. Xenon-135 has a microscopic absorption cross-section of 3.5×10^6 barns and a total fission product yield of 6.6%. Samarium-149 has an absorption cross-section of 42,000 barns and a total fission product yield of 1.4%. Xenon-135 is the more important of the two and we will first deal with the way it builds up with operation of the reactor.

Production of xenon-135

Xenon-135 (often simply referred to just as xenon) is produced in the fuel in two ways:

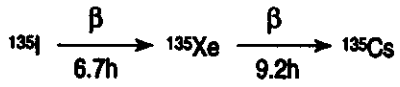
a) Directly from fission. About 0.3% of all fission products are Xe-135.

b) Indirectly from the decay of iodine-135, which is either produced directly as a fission product or from the decay of the fission product tellurium-135 via the following decay chain.

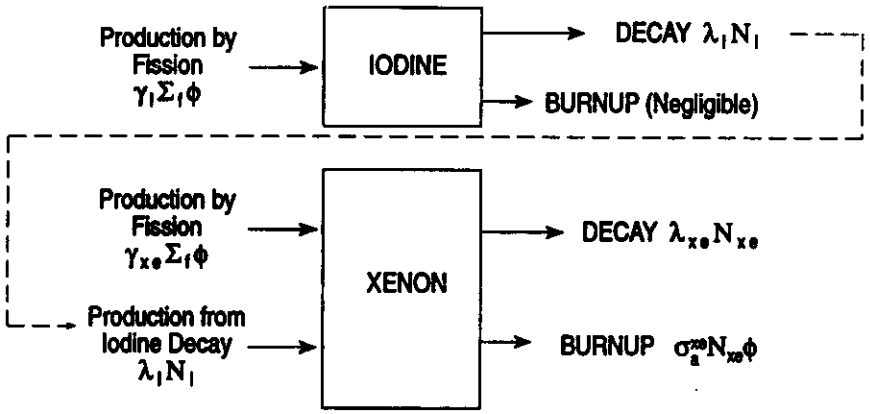
$$^{135}_{52}Te \xrightarrow[t_{1/2}=19s]{\beta,\gamma} {}^{135}_{53}I \xrightarrow[t_{1/2}=6.7h]{\beta,\gamma} {}^{135}_{54}Xe$$

Together, Te-135 and I-135 constitute about 6.3% of all fission products. Due to the short half-life of Te-135, we normally consider the entire 6.3% to be produced as I-135.

We now derive the equations that describe the buildup of I-135 and Xe-135 in the reactor when it is brought up to power. You may find it useful to refer to Figure 11.1 where the various terms describing the production and loss rates of the two isotopes are incorporated in a block diagram. The rates of production depend on the fission rate per unit volume, which is given by the product $\Sigma_f\phi$, where Σ_f is the macroscopic fission cross-section and ϕ is the average thermal neutron flux.



$\gamma_I = 0.063$ $\quad \gamma_{Xe} = 0.003$ $\quad \sigma_a^{Xe} = 3.5 \times 10^6$ b



$$\frac{d}{dt}(N_I) = \gamma_I\Sigma_f\phi - \lambda_I N_I$$

$$\frac{d}{dt}(N_{Xe}) = [\gamma_{Xe}\Sigma_f\phi + \lambda_I N_I] - [\lambda_{Xe} N_{Xe} + \sigma_a^{Xe} N_{Xe}\phi]$$

5% 95% 10% 90%

Figure 11.1: Production and loss rates of Iodine and Xenon

11.3.1.1 Iodine-135

Build-up of iodine-135

The rate of production per unit volume of I-135 from fission = $\gamma_I \Sigma_f \phi$ where γ_I (= 0.063) is the fission product yield of I-135 (that is, the fraction of fissions that gives rise to I-135).

There are two possible ways I-135 can be lost. One is by its decay to Xe-135, which is

Decay rate of I-135 per unit volume = $\lambda_I N_I$ where

λ_I is the decay constant of I-135 (2.87×10^{-5} s^{-1})

N_I is the concentration of I-135 atoms per cm^3.

The other possible loss mechanism is the burnup of I-135 by radiative capture, which is

Burnup rate of I-135 $= \sigma_a^I N_I \phi$

where σ_a^I is the microscopic absorption cross-section of I-135 for thermal neutrons. In practice, this is small enough (7 barns) that the burnup of I-135 can be neglected as a loss mechanism compared to its radioactive decay.

The net rate of change of iodine concentration at any time will be given by subtracting its loss rate from its production rate. We therefore have (see first block diagram in Figure 11.1)

$$\frac{d}{dt}(N_I) = \gamma_I \Sigma_f \phi - \lambda_I N_I \qquad (11.1)$$

11.3.1.2 Xenon-135

Build-up of xenon-135

For xenon-135, the equation is a little more complicated. First of all, since it is produced both directly as a fission product and as a result of iodine decay, we have two production terms:

Rate of production of Xe-135 per unit volume from fission = $\gamma_{xe}\Sigma_f\phi$

where γ_{xe} (= 0.003) is the fission product yield of Xe-135.

Rate of production per unit volume from decay of I-135 = $\lambda_I N_I$.

In this case, we must take account of two sources of loss. Both burnup and decay are important removal processes for Xe-135. The decay of Xe-135 is

$$^{135}_{54}Xe \xrightarrow[t_{1/2}=9.2h]{\beta,\gamma} {}^{135}_{55}Cs$$

The loss terms (per unit volume) are

Decay rate of Xe-135 $= \lambda_{xe} N_{xe}$

Burnup rate of Xe-135 = $\sigma_a^{xe} N_{xe} \phi$

where N_{xe} is the concentration of Xe-135 atoms per cm^3 and the decay constant $\lambda_{xe} = 2.09 \times 10^{-5}$ s^{-1}. The cross-sections of the Xe-136 formed by neutron capture and the Cs-135 created by Xe-135 decay are negligible compared with the cross-section of Xe-135.

The equation giving the net rate of change of the xenon concentration is therefore

$$\frac{d}{dt}(N_{xe}) = \left[\gamma_{xe}\,\Sigma_f\,\phi + \lambda_I N_I\right] - \left[\lambda_{xe} N_{xe} + \sigma_a^{xe} N_{xe}\phi\right] \qquad (11.2)$$

Looking first at equation 11.1, we see that if we start a reactor up from a condition where there is no I-135 present in the fuel, it will initially build up at a reasonably rapid rate, because the second term on the right hand side will be negligible compared with the production rate. As time passes, however, N_I will gradually increase, so that $\lambda_I N_I$ increases and the net rate of growth of iodine begins to fall. Eventually, N_I will reach a value such that $\lambda_I N_I = \lambda_I \Sigma_f \phi$ and the net rate of growth becomes zero. The I-135 is then said to have reached its equilibrium value. Under these conditions, equation 11.1 becomes

$$0 = \gamma_I \Sigma_f \phi - \lambda_I N_{Ieq}$$

where N_{Ieq} is the equilibrium concentration of I-135. Hence

$$N_{Ieq} = \frac{\gamma_I \Sigma_f \phi}{\lambda_I} \qquad (11.3)$$

Equilibrium I-135

The approach to equilibrium after reactor start-up is shown in Figure 11.2. You will no doubt see the resemblance to the graph we derived in Section 7.4.2 for the build up of Pu-239 to its equilibrium concentration. The equation for the buildup of I-135 as a function of time is

$$N_I = N_{Ieq}(1 - e^{-\lambda_I t})$$

The concentration will reach within 2% of its equilibrium value after 40 hours of reactor operation. Note that the equilibrium level of I-135 as given by equation 11.3 is ***directly proportional to the thermal neutron flux*** ϕ.

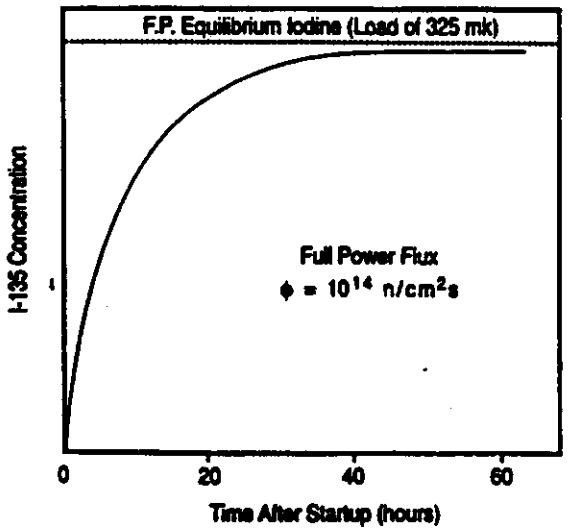


Figure 11.2: Buildup of I-135 towards equilibrium value

Now we are able to examine the behavior of xenon. The buildup of xenon is somewhat more complex than the buildup of iodine. Again, at equilibrium, we have

$$\frac{d}{dt}(N_{xe}) = 0$$

since production = loss. The I-135, which builds up somewhat more rapidly than xenon, will also be in equilibrium, so that we can substitute the expression on the right hand side of equation (11.3) for N_I in equation (11.2). When we make these substitutions, we find

$$\gamma_{xe}\Sigma_f\phi + \gamma_I\Sigma_f\phi = \lambda_{xe}N_{xe} + \sigma_a^{xe}N_{xe}\phi$$

Equilibrium Xe-135

Rearranging, the equilibrium Xe-135 concentration is

$$N_{xe\,eq} = \frac{(\gamma_{xe} + \gamma_I)}{\lambda_{xe} + \sigma_a^{xe}\phi}\Sigma_f \phi \qquad \textbf{(11.4)}$$

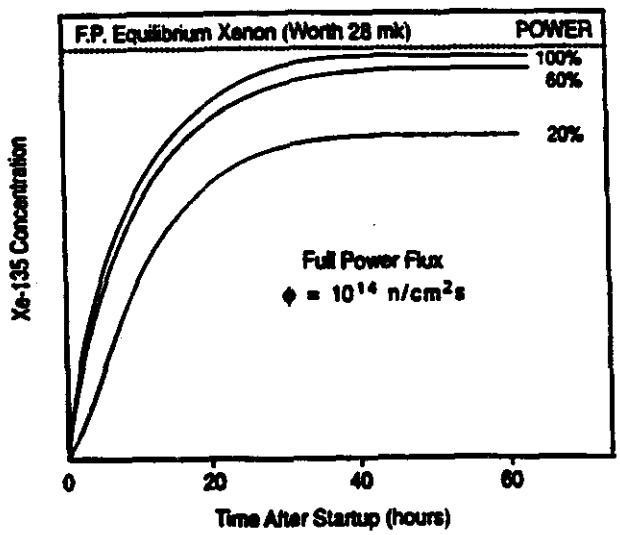


Figure 11.3: Buildup of Xe-135 towards equilibrium value

The buildup of Xe-135 is shown in Figure 11.3. Like the I-135, the Xe-135 reaches within 2% of its equilibrium value after 40 hours of reactor operation. We noted earlier that the equilibrium concentration of I-135 was directly proportional to the power level. The equilibrium concentration of Xe-135, on the other hand (at least in the large CANDU reactors), does not vary very much with power in the range from 50% to 100% of full power. We can see this by examining equation (11.4) for $N_{xe\,eq}$. Taking a typical full-power flux for a CANDU reactor of $\phi = 7 \times 10^{13}$ n/cm^2 s, the magnitudes of the two terms on the bottom line of the expression are

$$\lambda_{xe} = 2.09 \times 10^{-5} s^{-1}$$

Notes & References

$$\sigma_a^{xe}\,\phi = 3.5\times10^{6}\times10^{-24}\times7\times10^{13} = 24.5\times10^{-5}\,s^{-1}$$

Consequently, at fluxes close to the normal operating value, the first term can be ignored compared to the second and we can write

$$N_{xe\,eq} = \frac{(\gamma_{xe}+\gamma_I)\Sigma_f\,\phi}{\sigma_a^{xe}\phi} = \frac{(\gamma_{xe}+\gamma_I)\Sigma_f}{\sigma_a^{xe}}$$

Since the terms in ϕ cancel, we can say that the equilibrium xenon concentration is relatively independent of power level, at least within the range of 50% to 100% of full power.

11.4 REACTIVITY EFFECTS OF XENON

Xenon load

Owing to its very strong absorption, the xenon which is built up creates a large negative reactivity in the core. The reactivity worth of the Xe-135 is known as the **xenon load** (Δk_{xe}). The xenon load, which is simply proportional to the xenon concentration, varies with the (steady) power of the reactor as shown in Figure 11.4. As noted above, the reactivity associated with the equilibrium xenon does not alter much above 50% of full power. The reactivity worth of equilibrium xenon in a large CANDU at full power is approximately -28 mk.

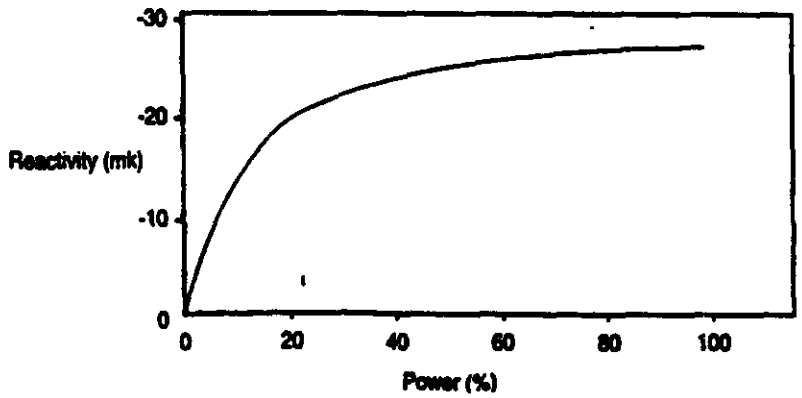


Figure 11.4: Xenon load as a function of reactor power

Iodine load

It is also common practice to express the concentration of iodine as ***iodine load*** in mk. It is important to realize that iodine alone is not a significant poison, so that there is no appreciable reactivity associated with it. The ***iodine load*** is defined as the reactivity that would be put into the reactor ***if all the iodine present were suddenly changed into xenon.*** Note this point carefully and understand that we are not talking about a real reactivity that exists in the system, but a potential reactivity that would only occur if the transformation of all the iodine to xenon were somehow to take place. A typical value of the iodine load is about -320 mk.

11.5 TRANSIENT XENON BEHAVIOUR

Reactivity arising from equilibrium xenon is easily compensated by designing the reactor to have sufficient positive reactivity to overcome the negative reactivity due to the xenon. This means that there must be a large potential excess reactivity in the system when there is no xenon present, which will be the case before the reactor has started to operate or after a long shutdown (when the xenon will have decayed away). We must be able to compensate for this excess reactivity. This is most commonly done by dissolving a neutron poison (boron or gadolinium) in the moderator and removing it as the reactor starts up and xenon begins to build. This addition of poison to the moderator on startup is called ***xenon simulation***.

Xenon transient

Although the equilibrium xenon can be handled as suggested above, a further problem is created when, following a shutdown after operation at power, xenon reactivity actually ***rises*** rapidly and passes through a peak that may last up to a couple of days. In order to see how this occurs, let's look back at equation (11.2), which describes how the xenon concentration varies as a function of time. What we have done below is to indicate underneath each term what its relative magnitude is for a CANDU which has been running steadily at full power long enough for equilibrium conditions to have been established.

$$\frac{d}{dt}(N_{xe}) = \left[\gamma_{xe}\Sigma_f\phi + \lambda_I N_I\right] - \left[\lambda_{xe}N_{xe} + \sigma_a^{xe}N_{xe}\phi\right]$$

5% 95% 10% 90%

If we look at the two production terms, it is easily shown that the production rate of xenon from iodine decay is much larger than its production rate directly as a fission product. If we substitute in the expression (equation 11.3) for the equilibrium iodine, the second term becomes $\gamma_I \Sigma_f \phi$, so that the ratio between the two production terms is just γ_f/γ_{xe}, or 0.063/0.003. Hence the 95% to 5% ratio. For the loss terms, we have already established that under full power conditions, the term λ_{xe} is only about one-tenth of the term $\sigma_a^{xe}\phi$. Consequently, burnup by neutron capture accounts for about 90% of the loss of xenon, while its own radioactive decay accounts for only about 10% of the loss.

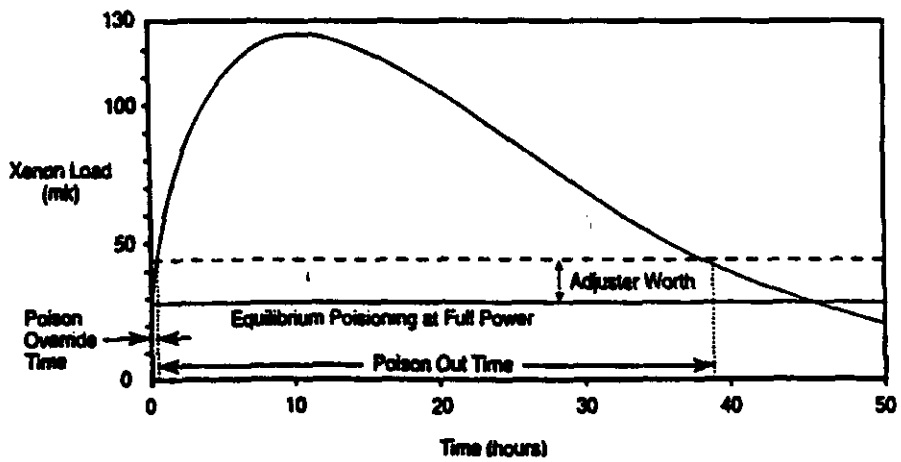


Figure 11.5: Xenon reactivity transient for a CANDU 600

Consider now what happens when the reactor is shut down after a long period of operation at full power. Since the flux ϕ drops to a near-zero value within a minute or so, the production rate of xenon drops by 5%, but initially its overall production rate remains at 95% of the steady state value. On the loss side, however, we lose 90% of the overall removal of xenon as the burnup drops to zero, leaving only the radioactive decay term.

Thus, immediately after shutdown, the removal rate drops to 10% of its steady state value, while production is still occurring at 95% of the steady state rate. The result is that the xenon concentration starts to rise quite rapidly, as shown in Figure 11.5. This cannot continue indefinitely, because there is only a limited quantity of iodine in the core and no more is being created once the reactor is shut down. The xenon therefore reaches a peak value about 10 hours after shutdown, and thereafter gradually decreases as the iodine that is feeding it decays.

Since the production rate of xenon after shutdown is proportional to the equilibrium iodine concentration and this, as shown earlier, is in turn proportional to the pre-shutdown flux, the height of the ***peak*** of the xenon load is strongly dependent on flux level. Thus, while the Pickering and Bruce reactors have a xenon peak of about 80 mk above the equilibrium xenon level, NPD, with a lower flux, had a peak only about 22 mk above an equilibrium value that was not much different from the bigger reactors. The CANDU 600 has a full power flux somewhat larger than at Pickering, so that the peak shown in Figure 11.5 is about 100 mk above equilibrium.

The ***rate of rise*** of the xenon load after a trip is also a function of the equilibrium conditions before the trip. In CANDU reactors, it is typically around 24 mk per hour for a trip from full power. If a reactor has a maximum available reactivity of, say, 15 mk, it must be brought back to high power within 30 minutes (the ***poison override time***) to burn out the xenon (by increased neutron absorption), or it won't be possible to start up again until the xenon transient has passed through its peak and decayed. When this happens, the reactor is said to have ***poisoned out***. The ***poison out time*** may be as high as 38 hours.

Xenon poison out

The most common way to provide the positive reactivity required for xenon override is to remove the adjuster rods normally kept inserted in the core. The use of adjuster rods carries a penalty in the form of a reduction in the attainable fuel burnup, as mentioned in Module 6, and so there is an incentive to keep the associated reactivity to the minimum necessary. In practice, the cost of providing the excess reactivity is usually optimized with respect to the energy production that would otherwise have been lost during the poison-out time.

So far, we have only discussed xenon transients occurring after a shut down from full power equilibrium conditions. In practical reactor operation, we are also interested in the transients after a shutdown from less than full power and after a step reduction in power. Solving the corresponding xenon equations is a laborious chore and computer codes are normally used. Figures 11.6 and 11.7 show the results of such calculations for a 200 MW reactor.

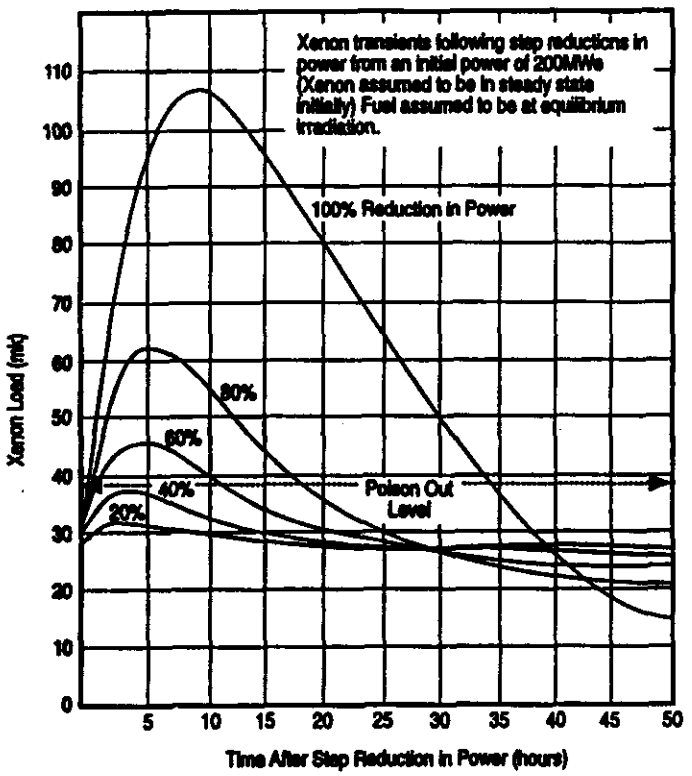
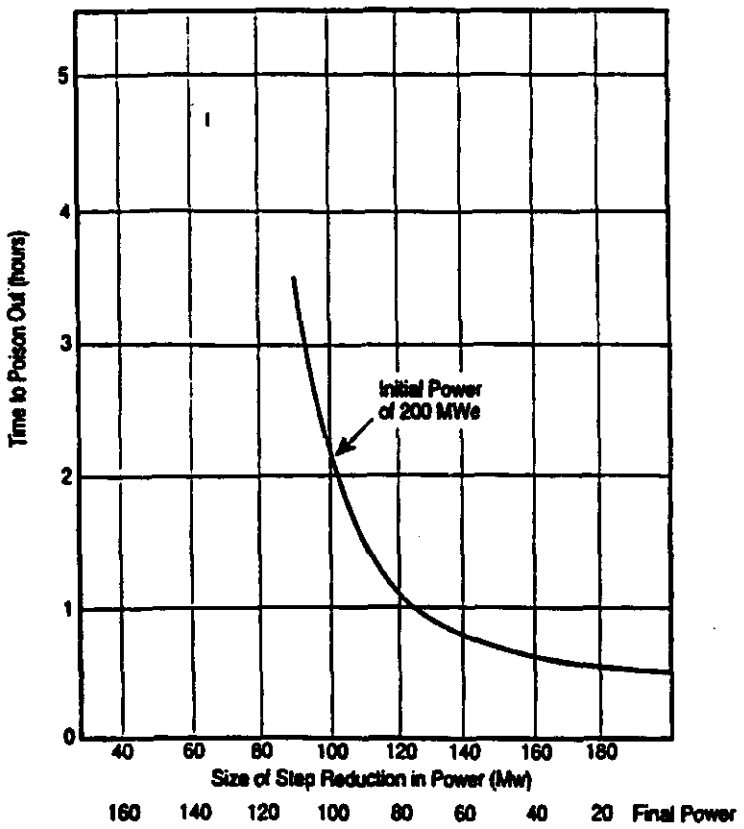


Figure 11.6: Xenon transients following step reductions in power from an initial power of 200 MWe. Xenon is assumed to be in steady state originally; fuel assumed to be at equilibrium irradiation.

Figure 11.6 shows the transients for 20, 40, 50, 80 and 100% power reductions from initial full power. For a reduction of, say, 40% (i.e., from 200 to 120 MW), the xenon removal by neutron capture will also decrease by 40% from its full-power value, but because xenon is still being removed, the transient will not reach its shutdown peak. Looking at the figure, you will see that for a 40% reduction, the available excess reactivity of ~10 mk is just sufficient to override the transient altogether. Ultimately, equilibrium will be restored and the xenon load will then be that corresponding to 60% of the full-power flux. The figure also shows that the rate of xenon buildup is less for a 60% reduction than for a 100% reduction, and that the poison override time will therefore be longer.

Figure 11.7 shows that this is true, namely, for a fixed amount of excess reactivity, the poison override time depends on the size of the power reduction. For example, the curve shows that a reduction of 120 MWe will result in a poison override time of 1 hour, while a reduction of 100 MWe will give an override time of 2 hours.



ADDITIONAL DATA				
INITIAL POWER LEVEL	STEP SIZE (MW)	TIME TO POISON (Hrs)	STEP SIZE (MW)	TIME TO POISON (Hrs)
120 MWe	80	2.25	120	1.0
160 MWe	80	2.5	160	0.7
180 MWe	80	5.4	80	2.33

Figure 11.7: Time to poison out versus size of step reduction in power from initial level of 200 MWe. Values for other initial power levels are shown in table. Fuel assumed at equilibrium irradiation.

enon after power increase

The converse of these curves also applies. For example, if the reactor is running at 140 MWe (at equilibrium) and is taken to 200 MWe, the immediate effect will be a gain in reactivity due to increased xenon burnup. At the same time, more iodine will be produced which will not appear as extra xenon production until later. As a result, the xenon curve will run through a minimum, and then xenon production will rise because of the increasing amount of decaying iodine. Eventually, the xenon concentration will attain the new equilibrium value corresponding to operation at 200 MW. The whole process is shown schematically in Figure 11.8. Normally, it does not present any operational problems.

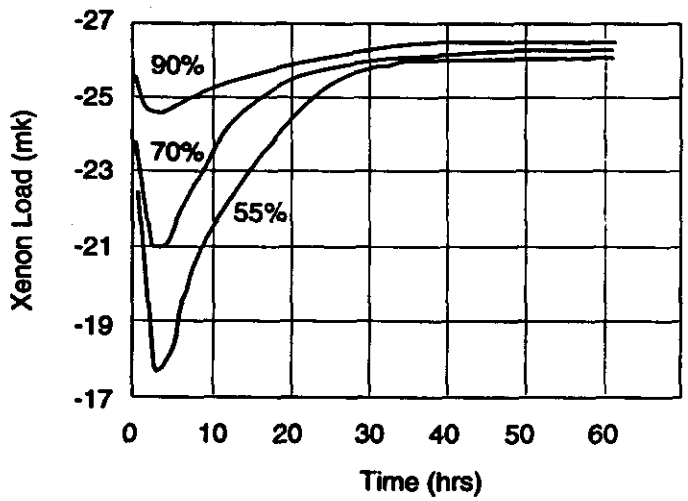


Figure 11.8 Variation in xenon load following increase in power from the various initial levels (% of full power) indicated.

11.6 XENON OSCILLATIONS

Xenon oscillations

Xenon reactivity is one of the factors that can cause a reactor to undergo periodic oscillations in flux level that must be controlled by a suitably designed control system. For the moment, let's ignore other possible sources of reactivity feedback in the reactor (we'll discuss some of these in the next section) and look at xenon in isolation. Let's take a reactor operating at full power and suppose that a small fluctuation takes place in the power with the effect of slightly increasing the flux throughout the system. Because the flux increases, a corresponding increase in the rate at which xenon is being burnt up occurs and this increases the reactivity of the core and thereby tends to produce a further increase in the flux. There is therefore a positive feedback effect which tends to push the power higher and higher unless some action is taken to reduce reactivity to compensate for the increasing burnup of xenon.

In practice, the control system will intervene to prevent this continual rise, and reduce the power. Even if it did not, the upwards drift would eventually stop because the increase in iodine concentration due to the higher flux level would lead to an increased input of xenon and thus to a reduction in reactivity. This would decrease the flux and therefore the burnup of the xenon, magnifying the negative reactivity. The flux would then start to drop and only recover when the reduced production of iodine at lower power resulted in a lower input of xenon. In this way, the reactor power could oscillate in amplitude with a period of several hours. Oscillations of this kind are easily prevented by having a control system that will react promptly to fluctuations in overall power and maintain it at a more or less constant level.

For a fairly small reactor, careful monitoring of the total reactor power to permit remedial action is all that is required to prevent oscillations. For large reactors, however, such as a full-scale CANDU, monitoring the overall power level is not enough because localized xenon oscillations can occur and drive power up in one region of the reactor and down in another, even though the total power remains constant. Let's take a reactor that has achieved equilibrium xenon and see exactly how localized oscillations can be generated.

Flux tilt

Suppose that, without changing the total power of the reactor, the flux is increased in one region of the reactor and simultaneously decreased in another region. This change from the desired normal distribution is called a ***flux tilt***. It may occur, for example, if control rods or similar mechanisms are inserted into one region and simultaneously withdrawn from another. In the region of increased flux, xenon now burns out more rapidly than it did before the change and its concentration decreases. The decrease in xenon concentration leads to a higher flux which again results in increased local xenon burnup, increased local reactivity, increased flux and so on.

Meanwhile, in the region of decreased flux, the xenon concentration increases due to its reduced burnup and to the continued decay of the existing iodine produced in the original, higher flux. This increased xenon concentration decreases reactivity in this region, which reduces the flux, and in turn increases the xenon concentration, and so on. The thermal flux, and hence the power density, decreases in this region and increases in the other, while the total power of the reactor remains constant.

Notes & References

These local power excursions do not continue forever. At the same time as the increased flux is causing xenon to burn out more rapidly in the high-flux region, it is also increasing the production of iodine. The decay of this enhanced iodine bank eventually leads to an increase in xenon concentration, reducing reactivity and thus the flux and power in that region. Likewise, in the region of reduced flux, the lowered production of iodine combined with the decay of accumulated xenon increases the local reactivity and reverses the flux and power transient in that region.

Xenon spatial oscillations

In this way and unless action is taken to control them, the flux and power of a reactor may oscillate between different regions (end to end or side to side). Calculations show that ***xenon spatial oscillations*** have a peak-to-peak cycle time of about 15 to 30 hours.

Conditions for spatial oscillations

This type of localized xenon oscillation can only take place in large reactors, by which one means reactors whose spatial dimensions are large in comparison with the diffusion length of the neutrons. With a small core, a disturbance started in one region will affect other regions because neutrons leaking out of the affected region will spread the disturbance to the rest of the core. In that case, as we mentioned earlier, a regulating system based on the overall power level will be adequate to prevent oscillations. When the dimensions of the reactor greatly exceed the distance travelled by the thermal neutrons during their lifetime (which is the case in a large CANDU), a disturbance which begins in one place will not spread its influence to a distant part of the core, so that the various regions act in a much more independent manner. Thus, if a flux increase occurs in one region due to a fuel change, for example, a control system based on maintaining the overall power constant will reduce the flux in another region to compensate. This would set up a xenon oscillation in the second region which would be exactly out of phase with that in the first region.

The other condition required to initiate spatial xenon oscillations is that the reactor operate at a high flux level. This is because the process is driven in the first place by the increased burnup of xenon that will occur when the flux is increased at some point in the reactor. In order for the xenon concentration to respond markedly to a change in flux, the burnup term in equation (11.2) must predominate over the decay term. We have already seen that this is indeed the case for a large CANDU, where the burnup term is usually about a factor of 10 larger than the other.

The CANDU, then, like several other types of power reactor, satisfies the two conditions required for the possible existence of spatial xenon oscillations. Since these can occur when the reactor is at constant (overall) power, they can continue unnoticed unless the flux and/or power density distributions are monitored at several points throughout the reactor, and localized absorbers are provided to adjust the local reactivity to counteract the flux tilts. Douglas Point at 200 MW(e) was the first CANDU to have regional absorbers to control xenon oscillations; it was equipped with four absorbers which in effect controlled four regions or zones in the reactor. Pickering at 540 MW(e) is quite a bit larger and so it is divided into 14 zones. Each zone has its own flux detectors whose output is used to adjust the amount of light water absorber in the zone control compartments. This design was retained for the Bruce and Darlington units and for the CANDU 600 reactors.

Zone Control System

It is important to realize that, even in the presence of a zone control system, it is still possible that xenon oscillations of sufficient magnitude to pose a risk of significant damage to the fuel can still occur. The severity of the flux tilt depends on the size of the reactivity perturbation which initiates the oscillation and on the depth of the compensating reactivity that can be provided by the zone control system. If the oscillation is large enough to cause the liquid zones to reach their operating limits, spatial control would be lost for that portion of the core. Continued operation with flux oscillations of such a magnitude could lead, at least, to a reactor overpower trip or, more seriously, to dangerously high local fuel temperatures and even fuel meltdown. Even if such severe consequences did not occur, the xenon oscillations would burden the core materials with unnecessary temperature cycling and could lead to premature materials failure.

11.7 SAMARIUM-149

The other fission product that is important enough to be discussed individually is samarium-149. It is formed in the fuel by the decay of neodymium-149 and promethium-149:

$$^{149}_{60}Nd \xrightarrow[t_{1/2}=1.7h]{\beta,\gamma} {}^{149}_{61}Pm \xrightarrow[t_{1/2}=53h]{\beta,\gamma} {}^{149}_{62}Sm$$

Production of samarium-149

One important difference between Xe-135 and Sm-149 is that samarium-149 is a ***stable isotope***, and will therefore remain in the core after shutdown rather than decaying away as xenon eventually does. Because it is stable, it can only be removed by the process of neutron capture with the reactor at power. The Sm-150 formed has a low absorption cross-section and its reactivity is therefore insignificant. Since Sm-149 has a much lower cross-section (4.2×10^4 barns) than Xe-135, it will take correspondingly longer to reach equilibrium (compare equation 7.7).

We can write down the equations describing the rate of change of Pm-149 and Sm-149 concentrations the same way we did for I-135 and Xe-135. The half life of Nd-149 is so short compared with Pm-149 that we lump its fission yield together with promethium to give a total yield (fraction of fissions giving rise to Pm-149) of 1.13%. Since the absorption cross-section of Pm-149 is low enough that its rate of burnup is negligible compared to its rate of loss by radioactive decay, the equation for the net rate of change of Pm-149 is identical in form to that of I-135 (equation 11.1). It will therefore build up to equilibrium in a similar way, except that it will take longer to reach equilibrium because of its greater half-life.

The equation for Sm-149 buildup is simpler than for Xe-135 (equation 11.2), because there is no direct production of samarium from fission and no loss by decay because it is stable. It will build up to equilibrium in about 300 hours of operation, to a reactivity value of approximately -5 mk. The time required to reach equilibrium is a function of the flux level, but ***the equilibrium samarium concentration is independent of the flux.***

As with xenon, the samarium concentration will increase after a shutdown. It continues to be produced by the decay of promethium but its burnup by neutron capture ceases when the flux disappears. The maximum samarium load after shutdown depends on the promethium load prior to shutdown. For larger CANDU reactors, the maximum samarium load is about 12 - 15 mk. The buildup is shown in Figure 11.9.

It is interesting to note that, although reactor design must allow for the equilibrium samarium load, the shutdown load does not cause any problems. There are two reasons for this:

1. By looking at the time scale of Figure 11.9, you will realize that the maximum samarium load will not appear until the xenon transient has long gone. There will be lots of reactivity available to deal with the samarium buildup when it occurs. You can also see that the increase in samarium load during the xenon poison override time is negligible, so that this doesn't present a problem either.

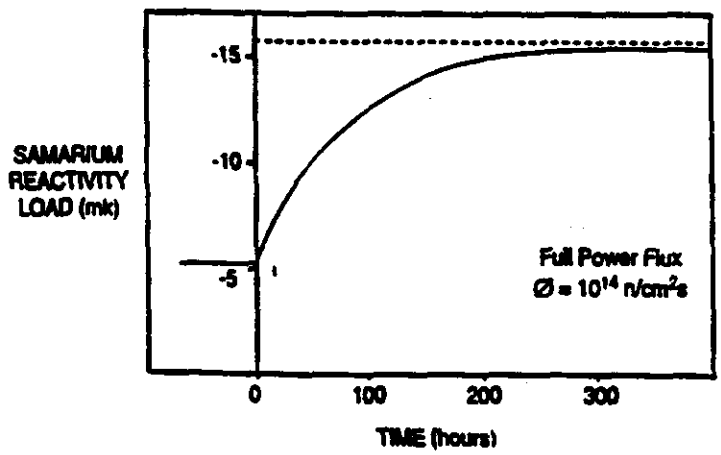


Figure 11.9: Increase in samarium load after shutdown

2. The rate at which samarium is formed after shutdown is governed by the Pm-149 half-life of 53 hours which, by coincidence, is almost the same as that of Np-239 (56 hours). You will recall (Section 2.8.3) that this Np-239 is the parent of the Pu-239 that adds reactivity to the system as it builds up in the fuel. After shutdown, the Pu-239 starts to increase above its pre-shutdown value because it is being formed by Np-239 decay, but is no longer being burnt up by neutron absorption. It turns out that the increased reactivity gained from the Pu-239 buildup more than compensates for the reactivity loss due to the increased Sm-149. The net result of the two effects together is a reactivity gain of several mk. This means that, on restart, the reactor will go critical a little earlier than otherwise might have been expected. Then, as conditions return to equilibrium, the loss in excess reactivity must be compensated by poison removal or refuelling.

ASSIGNMENT

1. Write the equations for the rates of change of the concentrations of Xe-135 and I-135. Explain what each term represents and give the magnitudes of the terms for the Xe-135 case. State the conditions where these magnitudes apply.

2. Explain why equilibrium xenon load changes very little when power is raised from 50% to 100%.

3. Explain why peak xenon after shutdown from 100% equilibrium will be nearly twice that after shutdown from 50% equilibrium.

4. Explain why there is a transient increase in xenon concentration after reactor shutdown, and how this increase depends on the operating power prior to shutdown.

5. Define iodine load and explain its significance.

6. **Note: This problem assumes some familiarity with the reactor regulating system, which has not yet been covered; details are given in Module 13.**

   The following is an operating procedure which is applied to a large CANDU reactor to extend the time to poison prior to entering a brief maintenance shutdown.

   i) Reduce reactor power to a value within the poison override capability (≈ 50% F.P.).

   ii) After the xenon load peaks (4-5 hours), increase the reactor power to 75% F.P.

iii) When all adjuster rods are in core and the average zone level is high, shut down the reactor.

The particular reactor uses liquid zone compartments worth 6 mk for fine power regulation, adjuster rods worth 18 mk for poison override, and has a full power equilibrium xenon load of 28 mk.

With regard to this procedure:

a) State the purpose of reducing reactor power in step (1), and explain why the power reduction achieves this purpose.

b) Explain how the operator determines that the xenon load has peaked before starting step (2).

c) i) State the purpose of increasing reactor power in step (2) and explain (in terms of the mechanisms of formation and removal of xenon) why this purpose is achieved when the reactor power is increased.

ii) State the likely reason why reactor power is not increased further than 75% F.P.

d) State the approximate value of xenon load when the reactor is about to be shut down in step (3). Justify your answer.

7. Explain how, in the absence of spatial control and protective mechanisms, xenon spatial oscillations could occur, and give the conditions that a reactor must satisfy if such oscillations are to occur.

Notes & References

8. Explain why the growth of Sm-149 after shutdown may be neglected in reactor design.

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