



8. Effects of ^{135}Xe

- ◆ **The xenon isotope ^{135}Xe plays an important role in any power reactor.**
- ◆ **It has a very large absorption cross section for thermal neutrons and represents therefore a considerable load on the chain reaction.**
- ◆ **The ^{135}Xe concentration has an impact on the power distribution,**
- ◆ **and in turn is affected by the power distribution, by changes in power, and by movements of reactivity devices.**



8.1 The Xe-I Kinetics

- ◆ The $^{135}\text{Xe}/^{135}\text{I}$ kinetics are shown schematically in Figure 8.1.
- ◆ ^{135}Xe is produced to some degree directly in fission, but mostly as the result of the beta decay of its precursor ^{135}I (which has a half-life of 6.585 hours).



8.1 The Xe-I Kinetics

- ◆ **^{135}Xe is destroyed in two ways:**
 - ♣ through its own radioactive decay (^{135}Xe has a half-life of 9.169 hours), and by absorption of neutrons to form ^{136}Xe ,
 - ♣ ^{135}I is a direct product of fission, but can also appear through the radioactive decay chain ^{135}Te to ^{135}Sb to ^{135}I .
- ◆ **^{135}Te and ^{135}Sb have half-lives which are very short (19.0 s and 1.71 s) compared to those of ^{135}I and of ^{135}Xe ;**
- ◆ **it is sufficient to model the decay of ^{135}Te and ^{135}Sb as “instantaneous”, and add their fission yields to that of ^{135}I .**



8.1 *The Xe-I Kinetics*

- ◆ The $^{135}\text{Xe}/^{135}\text{I}$ kinetics in any particular fuel bundle can thus be represented by the following equations:

$$\frac{dI}{dt} = \gamma_i \hat{\Sigma}_f \hat{\phi}_F - \lambda_1 I \quad (8.1)$$

$$\frac{dX}{dt} = \gamma_x \hat{\Sigma}_f \hat{\phi}_F + \lambda_1 I - \lambda_x X - \hat{\sigma}_X X \hat{\phi}_F \quad (8.2)$$

- ◆ where:



8.1 The Xe-I Kinetics

X = avge. conc. of ^{135}Xe in the bundle (atoms cm^{-3})

I = avge. conc. of ^{135}I in the bundle (atoms cm^{-3})

γ_x = direct yield of ^{135}Xe per fission

γ_I = direct yield of ^{135}I in fission, including yields of ^{135}Te and ^{135}Sb

λ_x = decay constant of ^{135}Xe in s^{-1}

λ_I = decay constant of ^{135}I in s^{-1}

$\hat{\phi}$ = bundle-average flux in the fuel ($\text{n}\cdot\text{cm}^{-2}\text{s}^{-1}$)

$\hat{\Sigma}_f$ = macroscopic fission cross section of the fuel (cm^{-1})

and

$\hat{\sigma}_x$ = microscopic ^{135}Xe cross section (cm^2)



8.1 The Xe-I Kinetics

- ◆ In the above equations, the term $\gamma_i \hat{\Sigma}_f \hat{\phi}_F$ gives the ^{135}I production rate,
- ◆ while $\lambda_i \text{I}$ gives the ^{135}I loss rate (and the production rate of ^{135}Xe by iodine decay).
- ◆ Similarly, the term $\gamma_x \hat{\Sigma}_f \hat{\phi}_F$ gives the production rate of ^{135}Xe due to direct fission, while $\lambda_x \text{X}$ gives its decay rate.
- ◆ The term $\hat{\sigma}_x \text{X} \hat{\phi}_F$ represents the “destruction” (burnout) rate of ^{135}Xe due to neutron capture.
- ◆ Because of the comparable magnitudes of the various terms, the ^{135}Xe concentration is very sensitive to changes in flux level.



8.1 The Xe-I Kinetics

- ◆ **The large absorption cross section of ^{135}Xe plays significant role in the overall neutron balance in the reactor,**
- ◆ **and thus directly affects the system reactivity, both in steady state and in transients.**
- ◆ **The $^{135}\text{Xe}/^{135}\text{I}$ kinetics also influences the spatial power distribution in the reactor.**



8.2 Reactor Startup

- ◆ **When a reactor is first started, or restarted after a long shutdown, the ^{135}Xe concentration will build up in all fuel bundles according to the equations derived above.**
- ◆ **In Figure 8.2, the variation of system reactivity as a function of time following startup is given for different final steady-state power levels.**
- ◆ **It can be seen that it takes ~ 40 hours for the ^{135}Xe concentration to fully reach equilibrium.**



8.3 *Steady-State Xenon Load*

- ◆ At steady state the time derivatives dI/dt and dX/dt are zero.
- ◆ The above equations can then be solved to give the steady state concentrations of ^{135}I and ^{135}Xe (I_{ss} and X_{ss}):

$$I_{ss} = \frac{\gamma_i \hat{\Sigma}_f \hat{\phi}_F}{\lambda_i} \quad (8.3)$$

$$X_{ss} = \frac{(\gamma_i + \gamma_x) \hat{\Sigma}_f \hat{\phi}_F}{\lambda_x + \hat{\sigma}_x \hat{\phi}_F} \quad (8.4)$$



8.3 *Steady-State Xenon Load*

- ◆ It is obvious from these equations that,
- ◆ as a function of an increasing fuel flux ,
- ◆ the steady-state concentration of ^{135}I increases indefinitely,
- ◆ while in contrast that of ^{135}Xe tends to an **asymptotic** value which will be denoted $X_{ss,\infty}$:

$$X_{ss,\infty} = \frac{(\gamma_i + \gamma_x) \hat{\Sigma}_f}{\hat{\sigma}_x} \quad (8.5)$$

- ◆ This asymptotic nature of the variation of X_{ss} with $\hat{\phi}_F$ is the reason why ^{135}Xe is termed a “saturating” fission product. (Other saturating fission products are ^{105}Rh , ^{149}Sm , ^{151}Sm , etc.)



8.3 Steady-State Xenon Load

- ◆ **The limiting ^{135}Xe absorption rate at very high flux levels leads to a maximum reactivity of ~ -30 mk.**
- ◆ **In CANDU the equilibrium xenon load is approximately -28 mk.**
- ◆ **The flux level at full power in CANDU is such that the ^{135}Xe concentration is about 95% saturated, i.e., the average ^{135}Xe concentration is equal to about 95% of the value in an infinite flux.**
- ◆ **However, the steady-state ^{135}Xe concentration is not uniform in the core, but varies with flux according to Eq. (8.4). This is discussed in greater detail in Section 8.6 below.**



8.4 Effect of Power Changes on Xenon Concentration

- ◆ **Due to the presence of the term $\sigma_x X \hat{\phi}_F$,**
- ◆ **the variation of the ^{135}Xe concentration with flux is non-linear.**
- ◆ **The ^{135}Xe reactivity following power (flux) changes will depend on:**
 - ♣ **the starting power level,**
 - ♣ **the time at that level,**
 - ♣ **the new power level, and**
 - ♣ **the time spent at the new power level.**



8.4 Effect of Power Changes on Xenon Concentration

- ◆ **Generally speaking, when the power is reduced from a steady level, the ^{135}Xe concentration increases at first.**
- ◆ **This is due to the fact that ^{135}Xe is still being produced by the decay of ^{135}I ,**
- ◆ **but its burnout rate (by neutron absorption) is decreased because of the reduced neutron flux (reduced power).**



8.4 Effect of Power Changes on Xenon Concentration

- ◆ **However, after a certain period (depending on the initial and final power and the rate of power reduction)**
- ◆ **the ^{135}I decay rate decreases sufficiently (due to the lower fission rate)**
- ◆ **that the rate of ^{135}Xe production drops below the rate of ^{135}Xe decay (and burnout).**
- ◆ **At this time, then, the ^{135}Xe concentration reaches a peak value and starts to decrease towards a new (lower) steady-state level.**



8.4 Effect of Power Changes on Xenon Concentration

- ◆ **Conversely, when the power is increased from a steady level,**
- ◆ **the ^{135}Xe concentration will first decrease,**
- ◆ **and then go through a minimum**
- ◆ **and start increasing again to a higher steady-state level.**



8.4 Effect of Power Changes on Xenon Concentration

- ◆ Fig. 8.3 shows some typical reactivity variations due to ^{135}Xe following step reductions in power.
- ◆ Very similar variations, but in the opposite direction, ensue upon step increases in power.
- ◆ The quantitative effects will be different at different points in the core, due to the initial non-uniform distribution of ^{135}Xe .
- ◆ Thus, for an accurate assessment of xenon transients on the power distribution, a point-kinetics treatment is generally inadequate, and calculations in three dimensions will be required.



8.5 Xenon Transient Following a Shutdown

- ◆ **Following a reactor shutdown, the burnout of ^{135}Xe stops,**
- ◆ **whereas the production by means of ^{135}I decay continues for several hours.**
- ◆ **The net result is that there is an initial increase in ^{135}Xe concentration and a decrease in core reactivity.**
- ◆ **If the reactor is required to be started up shortly after shutdown, extra positive reactivity must be supplied.**
- ◆ **The ^{135}Xe growth and decay following a shutdown for a typical CANDU is shown in Figure 8.4.**



8.5 Xenon Transient Following a Shutdown

- ◆ It can be seen that, at about 10 hours after shutdown,
- ◆ the reactivity worth of ^{135}Xe increases to several times its equilibrium full-power value.
- ◆ At ~35-40 hours the ^{135}Xe has decayed back to its pre-shutdown level.
- ◆ If it were not possible to add positive reactivity during this period, every shutdown would necessarily last some 40 hours, when the reactor would again reach criticality.



8.5 Xenon Transient Following a Shutdown

- ◆ **To achieve xenon “override” and permit power recovery following a shutdown (or reduction in reactor power), the CANDU-6 adjuster rods are withdrawn to provide positive reactivity.**
- ◆ **It is not possible to provide “complete” xenon override capability, this would require > 100 mk of positive reactivity.**
- ◆ **The CANDU-6 adjuster rods provide approximately 15 milli-k of reactivity, which is sufficient for about 30 minutes of xenon override following a shutdown.**



8.6 Effects of Xenon on Power Distribution

- ◆ **Xenon plays a role in the core power distribution.**
- ◆ **First, on the steady-state power distribution:**
- ◆ **Because the steady-state ^{135}Xe concentration depends on the flux (Eq. 8.2),**
- ◆ **high-power bundles will have a higher xenon load, and therefore a lower reactivity, than low-power bundles of the same irradiation.**

(cont'd)



8.6 Effects of Xenon on Power Distribution

- ◆ The effect of xenon is therefore to **flatten** the steady-state power distribution:
- ◆ The reduction in the maximum bundle power due to the local ^{135}Xe concentration can be of the order of 5%.
- ◆ For maximum channel power, ~3%.
- ◆ Thus xenon helps to increase the margin between peak powers and licensed limits.
- ◆ The xenon effect should be taken into account when accurate calculations are desired.



8.6 Effects of Xenon on Power Distribution

- ◆ **The xenon effect also plays a role after refuelling:**
- ◆ **Fresh bundles introduced into the reactor have no xenon (or other fission products) at first.**
- ◆ **Fig. 8.2 shows it takes a day or so for the xenon to build to near saturation .**
- ◆ **Thus, the power of these fresh bundles is high at first and subsequently decreases, by perhaps several per cent, to their equilibrium value.**



8.6 Effects of Xenon on Power Distribution

- ◆ **Also, bundles which are shifted along the refuelled channel experience a change in power.**
- ◆ **In these bundles, corresponding to the specific power change (decrease or increase),**
- ◆ **there is a xenon transient similar to those in Fig. 8.3 (or the “opposite”).**
- ◆ **This effect is not limited to shifted bundles, but occurs in any bundle whose power is affected by the channel refuelling operation, e.g. bundles in neighbouring channels.**



8.6 Effects of Xenon on Power Distribution

- ◆ **Transient-xenon effects due to refuelling are perhaps not always taken into account in routine core-follow calculations,**
- ◆ **but need to be captured when it is desired to perform the most accurate simulations,**
- ◆ **and to properly monitor the margin between peak powers and licensed limits.**



8.6 Effects of Xenon on Power Distribution

- ◆ **The RFSP history-based local-parameter methodology can simulate**
- ◆ **the spatially non-uniform effects of saturating-fission-product kinetics**
- ◆ **for both Xe-I and other fission-product pairs (e.g. Sm-Pm)**
- ◆ **in both steady-state and transient situations,**
- ◆ **by recalculating the ^{135}Xe concentration individually in every bundle, and therefore the effect on the lattice properties and on the core power distribution.**



Summary

- ◆ ^{135}Xe is an important poison, which makes itself felt at all times.
- ◆ Its spatial and time effects must be taken into account when accurate fuel-management calculations are required.