8. Effects of 135Xe

- 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}Xe/^{135}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}Xe/^{135}I kinetics in any particular fuel bundle can thus be represented by the following equations:**

$$\frac{dI}{dt} = \gamma_i \hat{\Sigma}_f \hat{\phi}_{\mathrm{F}} - \lambda_{\mathrm{i}} I \qquad \textbf{(8.1)}$$

$$\frac{dX}{dt} = \gamma_x \hat{\Sigma}_{\mathrm{f}} \hat{\phi}_{\mathrm{F}} + \lambda_i I - \lambda_x X - \hat{\sigma}_X X \hat{\phi}_{\mathrm{F}} \qquad \textbf{(8.2)}$$

- **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 (n.cm^{-2}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 λ_iI 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 λ_xX gives its decay rate.
- The term $\hat{\sigma}_x X \hat{\phi}_F$ 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}Xe/^{135}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}):

$$I_{ss} = \frac{\gamma_i \, \hat{\Sigma}_{\mathrm{f}} \, \hat{\phi}_{\mathrm{F}}}{\lambda_{\mathrm{i}}} \qquad (8.3)$$

$$X_{ss} = \frac{\left(\gamma_i + \gamma_x\right) \hat{\Sigma}_f \, \hat{\phi}_{\mathrm{F}}}{\lambda_{\mathrm{x}} + \hat{\sigma}_x \, \hat{\phi}_{\mathrm{F}}} \qquad (8.4)$$

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** $X_{ss,\infty}$ **:**

$$X_{ss,\infty} = \frac{\left(\gamma_i + \gamma_x\right) \hat{\Sigma}_{\mathrm{f}}}{\hat{\sigma}_{\mathrm{x}}} \qquad \textbf{(8.5)}$$

- **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.