20 Xenon: A Fission Product Poison

Many fission products absorb neutrons. Most absorption cross-sections are small and are not important in short-term operation. Xenon-135 has a cross-section of approximately 3,000,000 barns, over 4000 times that of U-235. That is, each atom of xenon-135 absorbs as many neutrons as 4000 U-235 atoms. About 6.6% of all fissions produce a nuclide of Xe-135, either directly as a fission product or indirectly as a fission product daughter. Xenon is a major problem in our reactors because of its remarkable neutron absorption and high yield.

20.1 Xenon Production

Xe-135 is produced directly in only 0.3% of all U-235 fissions. The following example is typical:

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{99}_{38}Sr + {}^{135}_{54}Xe + 2\,{}^{1}_{0}n + \gamma $$

Xenon-135 is mainly produced as a fission product daughter, by iodine decay as follows:

$$ {}^{135}_{53}\mathrm{I} \xrightarrow[T_{1/2}\,=\,6.6\,\mathrm{hr}]{} {}^{135}_{54}\mathrm{Xe} + \beta $$

Iodine-135 is produced in 6.3% of U-235 fissions. Thus, iodine decay accounts for about 95% of total xenon production. (6.3/6.6 = 0.95). Iodine-135 does not absorb neutrons.

20.2 Xenon Loss

Xenon is removed from the reactor by decay as follows:

$$ {}^{135}_{54}\mathrm{Xe} \xrightarrow[T_{1/2}\,=\,9.1\,\mathrm{hr}]{} {}^{135}_{55}\mathrm{Cs} + \beta $$

or by neutron absorption (radiative capture):

$$ {}^{1}_{0}n + {}^{135}_{54}Xe \rightarrow {}^{136}_{54}Xe + \gamma $$

The rate of burnout depends on the neutron flux. For a CANDU at full power, neutron absorption accounts for about 90% of Xe-135 loss, decay for only 10%. Cesium-135 and xenon-136 do not absorb neutrons.

20.3 Equilibrium Xenon Load

There is no xenon in the fuel of a reactor that has been shut down for a long time (or has never been operated). Xenon slowly builds to an equilibrium level after the reactor is started. The equilibrium level depends on the steady state reactor power. Figure 20.1 shows xenon load versus time for various power levels. For CANDU reactors at full power, xenon load builds to about 28 mk of negative reactivity in 35 hours or so.

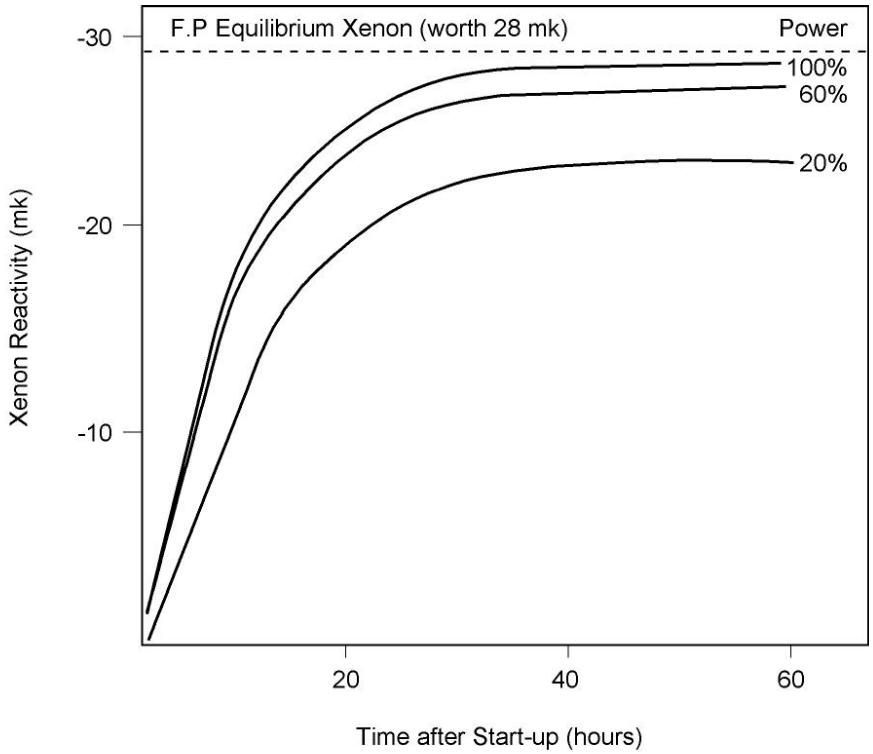

Figure 20.1
Xenon Build-up to Equilibrium

This negative reactivity (-28 mk) is always present in normal steady operation except during the first several hours after start-up. The reactor design includes enough excess positive reactivity to compensate for the normal -28 mk load.

When the normal xenon load is not present, operations must accommodate the excess positive reactivity with neutron absorbing chemicals. Soluble poison (boron or gadolinium) added to the moderator compensate for the missing xenon. As xenon concentration increases, burnout, or ion exchange purification remove the poison.

20.4 Xenon Transients

After operating for around 35 hours, xenon is near its equilibrium level. It then causes problems only if the reactor power is changed. For example, consider what happens to the production and loss of xenon-135 immediately after a reactor trip (or any fast power reduction to 0%).

a) Production:

- from fission (5%) - stops immediately
- from decay of iodine (95%) – continues

Result—on the short term, most of the production continues.

b) Loss:

- by decay (10%) - continues
- by neutron absorption (90%) - stops immediately

Result—on the short term, most of the removal stops.

The consequence of continued production without removal is a dramatic increase in xenon concentration immediately following a trip. Figure 20.2 is a graph of xenon load versus time after a trip from full power.

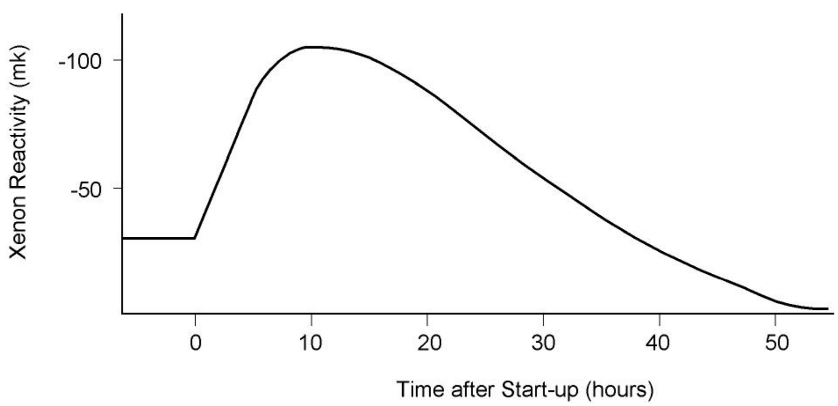

Figure 20.2
Behaviour of Xenon

Notice that negative reactivity from xenon peaks about 10 hours after a full shutdown, at a level much higher than the equilibrium 28 mk load. At the peak of the transient, the decay of Xe-135, which has increased because there is more xenon, matches the production of xenon by iodine decay, which has decreased because there is now less iodine. Iodine decay continually decreases, reducing xenon production. When the peak has passed, xenon decay exceeds production, and the curve gradually falls back towards normal and lower.

Any power reduction causes a transient xenon peak. The smaller the power reduction the smaller the peak, and the earlier it occurs. For example, on a power reduction from 100% to 60%, there is still an initial excess of production over loss, but significant neutron flux remains to burn out the xenon. The peak height and its duration are reduced, and the peak occurs earlier. Figure 20.3 includes a typical reactivity variation for a rapid power reduction (stepback) to 60%.

On a power increase after steady, low-power operation (say from 60% to 100%) the reverse effect occurs. Xenon burns out rapidly while production from iodine decay continues low. Reactivity increases and the control system must insert negative reactivity to compensate. Adding poison to the moderator supplements this as needed.

20.5 Poison Prevent and Poison Override

Withdrawing adjuster rods from the reactor core contributes positive reactivity, up to a maximum of 15 or 20 mk depending on the particular reactor. Excess positive reactivity is required to keep the reactor operating during small xenon transients. As Figure 20.3 shows, the adjusters can accommodate a stepback to 60%.

If the negative reactivity due to xenon exceeds the available adjuster positive reactivity, the reactor goes sub-critical with no way to restart it. We say it is poisoned out. Figure 20.3 shows that on a trip from full power, a reactor that is poisoned out cannot be restarted until 35 hours or so after the trip, when xenon has decayed to near the –28 mk equilibrium level.

Holding reactor power near 60% (or higher) prevents a poison out. It is important to realize that on a turbine trip it may be economically sound to keep the reactor operating and to exhaust steam to a condenser (or the atmosphere). We call this mode of operation poison prevent.

Thirty-five to forty minutes after a trip the negative reactivity from xenon exceeds the positive reactivity of the adjusters. (See figure 20.3 again.) If the reactor is started up during the 35 to 40 minute poison override time and brought up to power before poisoning out, the xenon will be burned up rapidly and a poison out may be prevented.

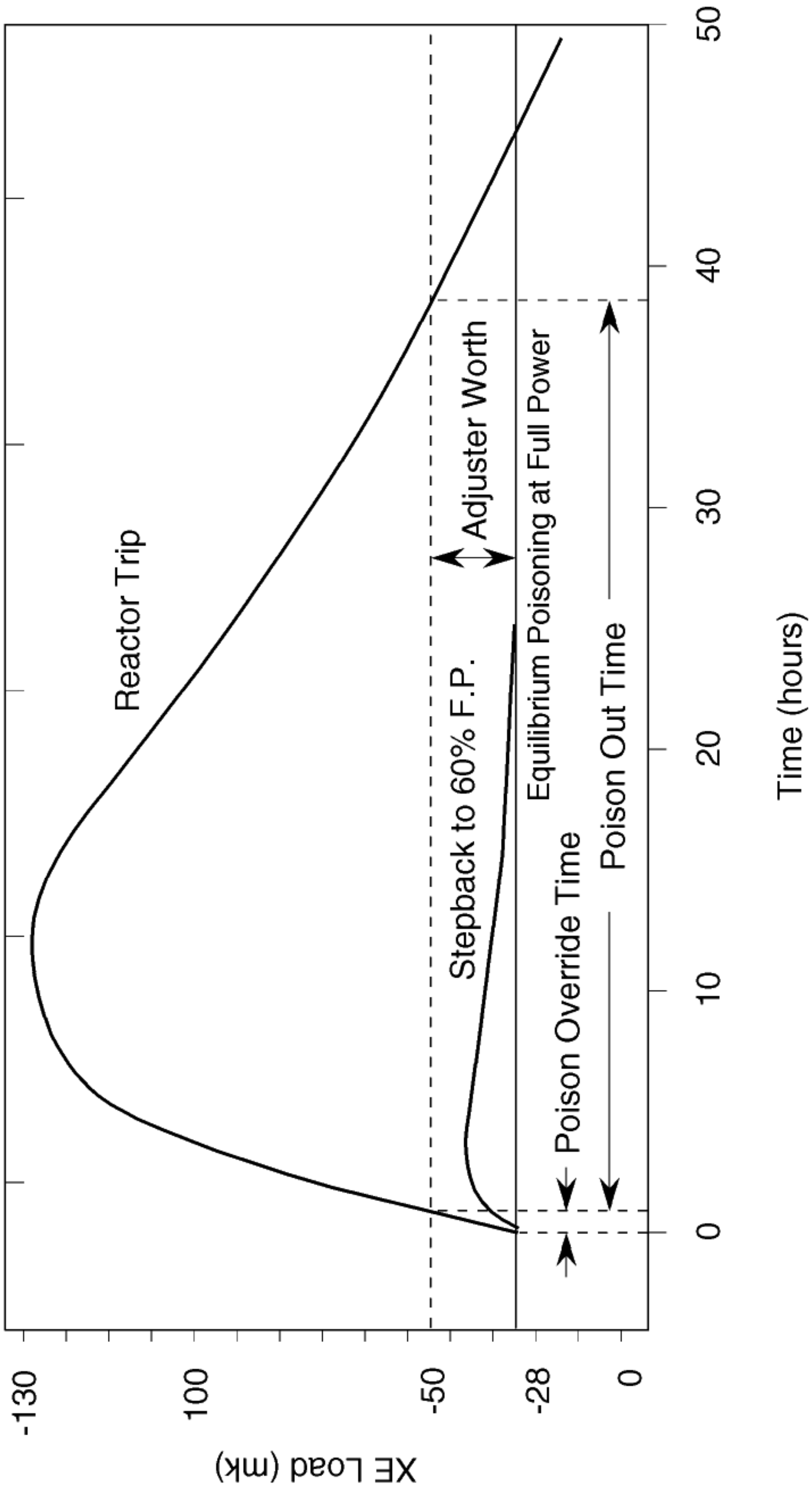

Figure 20.3
Transient Xenon Reactivity

Poison override is possible in principle, and is part of the reactor design, but is usually not practical. Before restarting the reactor following a trip, it is important to find the cause of the trip and eliminate the fault. A number of checks are required before a trip is judged to be spurious (that is, a trip that does not occur in response to an actual failure). The control room staff must make the decision to try to restart in about 20 minutes because the adjusters drive out slowly. Repairs or checks following a trip usually take longer than this. Operating procedures that do not allow the operators to try to "beat the poison out" remove the temptation to take short cuts.

20.6 Other Effects

In a large, high flux reactor, xenon may cause flux increases in one part of the reactor while flux is decreasing elsewhere. Instead of the flat flux shape illustrated previously, transient peaks and valleys occur. This operational problem will be discussed more in future modules.

20.7 Assignment

1. Sketch the behaviour of xenon on a reactor trip from full power.

2. Explain why a xenon poison out occurs.

3. Discuss the production and loss of xenon including the relative magnitude of each term for the following situations:
   (a) on start up,
   (b) on a power decrease from steady full power,
   (c) on a power increase from steady 60% power.

4. What features of xenon-135 and its production make it the most significant fission product in terms of its reactivity effect.