Nuclear Theory - Course 227

XENON POISON AND ITS EFFECTS ON REACTOR OPERATION

During the discussions on reactor control and reactivity changes, it was mentioned that the methods used for control would have to compensate for the gradual decrease in reactivity that occurs in a reactor. Such a continual decrease in reactivity may be due to a number of factors, the most important of which are: -

(1) using up or burning the U-235

(2) build up of fission products in the fuel.

The gradual decrease in reactivity due to these effects is compensated for by on-power refuelling, ie, regular replacement of used fuel with new fuel to maintain the amount of U-235 in the reactor and limit the amount of fission products. Some fission products, on the other hand, are strong absorbers of neutrons and require special compensation. Materials which absorb neutrons and therefore leave fewer neutrons to cause fissions are called POISONS. These fission products are therefore sometimes called fission product poisons.

In this lesson, we will discuss how these fission product poisons build-up in the reactor and how the resulting decrease in reactivity is counteracted.

The Build-up of Fission Product Poisons

Many fission products are strong absorbers of neutrons but the most important, by far, is Xenon-135. It is so much more important that the study and considerations of Xenon Poison are normally dealt with separately from other fission products. We will first consider the growth of Xe-135 in the reactor.

Xenon-135 is produced, in the fuel, in two ways: -

(1) directly as a fission product

(2) indirectly as a daughter of Iodine-135 which is, in turn, produced as a fission product or from the decay of the fission product Tellurium-135. The decay chain would be: -

$$Te^{135} \xrightarrow{\beta^-} I^{135} \xrightarrow{\beta^-} Xe^{135}$$

The half life of Te-135 is much less than either I-135 or Xe-135 and is therefore ignored in the remainder of the lesson when time factors are considered.

About 95% of Xe-135 is formed as a result of Iodine decay and only 5% of it is formed as a fission product.

If Xe-135 was continually produced, in the fuel, in this way and none of it was removed, its concentration would continually increase. Eventually, its absorption of neutrons would prevent the chain reaction from being maintained, however large the reactor might be. Fortunately, Xe-135 is also removed in two ways: -

(1) by decaying to Caesium-135, (which is not regarded as a poison), according to the reaction: -

$$Xe^{135} \xrightarrow{\beta^-} Cs^{135}$$

(2) by capturing thermal neutrons and changing to Xe-136 (which is again less of a problem).

$$Xe^{135} + n^1 = Xe^{136}$$

Here, then we have Xe-135 being produced in two ways and being removed in two ways. To understand what happens, let us compare the Xenon build-up to a can being filled with water. Fig. 1 shows the arrangement for filling the can. The build-up of Xe-135 is represented by the rise in the level of the water in Can A. Can A is filled directly by the small line on the left, which represents the direct formation of Xe-135 as a fission product.

Can A also receives water from Can B. The line passing water from Can B to Can A represents the formation of Xe-135 from I-135. So the rise in the water level in Can B represents the increase in I-135 in the reactor while the line filling Can B represents the production of I-135 from the decay of tellurium.

Water leaks out of Can A through two lines which represent the loss of Xe-135 by decay and by neutron capture.

Suppose that, to start with, both cans are empty. This condition represents the fuel with no iodine or Xenon in it. The reactor is now started up and is operating at steady power. Right away Te-135 is formed, which almost immediately starts decaying into I-135 and Can B starts to fill up.

Water also starts flowing directly into Can A through the small line since a little Xe-135 is being produced as a fission product. After a slight delay, water starts running from Can B into Can A, but the water level in B rises because water is running in faster than it runs out, ie, I-135 is being formed faster than it decays to Xe-135. As the level in Can B rises, the water runs out faster because of the greater head of water, until, eventually, the water runs out of B as fast as it runs into it. From this point on, the level in B remains steady or the I-135 has reached an equilibrium level. It decays at the same rate, as it is formed, and its concentration in the fuel does not therefore increase or decrease.

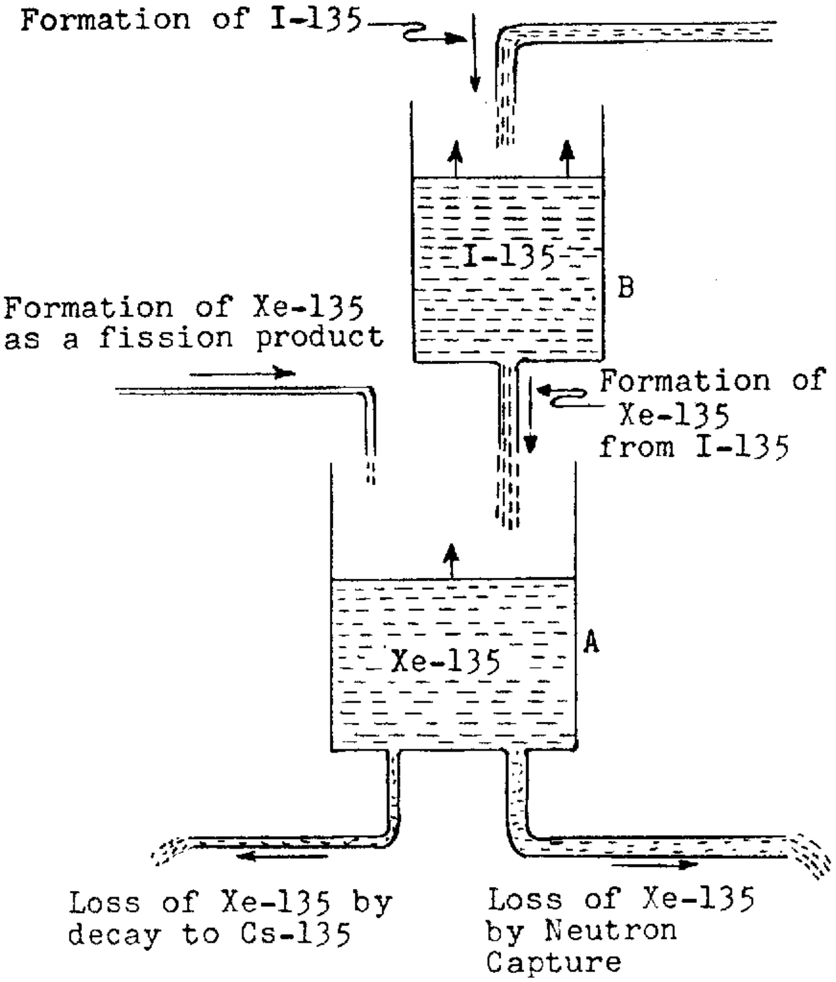

Fig. 1

Meanwhile, Can A is being filled from Can B and by the small direct line. Soon water starts leaking out of Can A through the Xe decay line and the neutron capture line. However, water flows into Can A faster than it leaks out and the water level in A rises, ie, the Xe-135 concentration is increasing. But the higher the level in A, the faster the flow out of A and the slower A fills up. Eventually, the level is such that the water flows out as fast as it flows in and the level in A then remains steady. What we are saying, then, is that the Xe-135 concentration in the fuel increases until the removal of Xenon, by decay and neutron capture increases to the point where it exactly balances the production of Xenon, as a fission product and by decay of I-135. From then on, the Xe-135 concentration remains constant.

The build up of Xe-135 is shown graphically in Fig. 2.

It must be remembered that the final equilibrium value of Xe-135 depends upon the neutron flux and hence on the power at which a reactor is operating. The rate of buildup to equilibrium is almost independent of flux over the range of interest. It takes several days to reach a true equilibrium due to the exponential shape of the curve but buildup during the early part of the curve is fairly rapid. In a typical power reactor the Xe-135 reaches 50% of equilibrium in 10 hrs and 90% of equilibrium in 24 hrs of steady power operation.

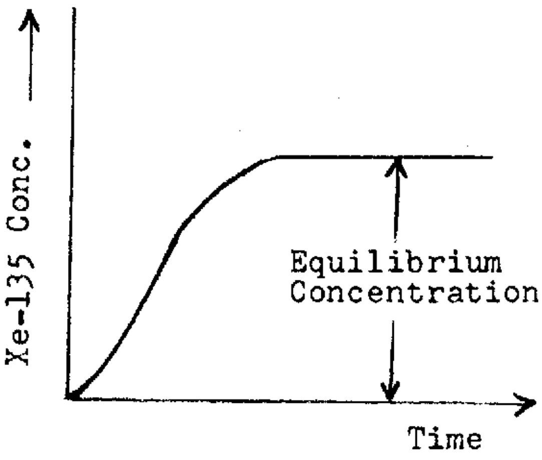

Fig. 2

Consequences of Xenon Poison Buildup

Xenon 135, and other fission products, are poisons which absorb neutrons and therefore, reduce the multiplication factor k, and reactivity, δk. As Xe-135 increases from zero to equilibrium concentration, it reduces the reactivity by 20, 25 or even 30 mk. That is, it introduces this amount of negative reactivity into the reactor, just as surely as if boron or cadmium rods has been inserted into the reactor. There are two important consequences of this loss of reactivity: -

(1) The reactor must be big enough so that, as the Xe-135 increases and the reactivity decreases, the regulating system must be able to increase the reactivity by the same amount. That is, enough reactivity must be built into the reactor to balance the loss in reactivity due to equilibrium Xenon poison. This loss in reactivity, due to equilibrium Xenon, is known as the EQUILIBRIUM XENON REACTIVITY LOAD.

With a reactor which uses moderator level for coarse reactivity control, this means that when the Xenon concentration is zero, the critical moderator level will be much lower than it will be at equilibrium Xenon concentration, so that the moderator can rise to compensate for the Xenon load buildup.

(2) With the moderator level low, before the Xenon buildup starts, some fuel may not be covered by the moderator and reactor operating power may be limited to well below full power. In fact the reactor may not be able to operate at full power for 60 or 70 hours after start-up, ie, until the equilibrium Xenon concentration is reached at various power levels which keeps the moderator level rising.

This is obviously a disadvantage and has to be overcome if possible. To overcome this disadvantage, what is done is to introduce a neutron absorber, like cadmium sulphate, into the moderator so that the reactor has to operate full of moderator to overcome the loss in reactivity due to the cadmium sulphate. As the Xenon load increases, the cadmium sulphate is removed and the moderator remains at a high level. There is, therefore, no loss of production of power.

Xenon Build-up After Reactor Shutdown

Let us now suppose that the reactor trips and is shut down. What happens to the Xenon concentration? Going back to Fig. 1, we see that the formation of I-135 stops and so does the direct formation of Xe-135 as a fission product. Thus, Can B is no longer being filled and nor is Can A directly. However, there is water already in Can B (ie, there is I-135 already formed in the fuel), and Can B continues to empty into Can A.

What of the leakage from Can A? Since the reactor is shut down, there are no neutrons to be captured in Xe-135 and there is no loss of Xe-135 by neutron capture. Xe-135 continues to decay to Cs-135 and so there is loss from Can A through the smaller pipe only. The situation, as it now exists, is shown in Fig. 3.

Initially, the flow into Can A is faster than the leakage flow out, and the level starts to rise above the previous equilibrium, ie, Xe-135 is being produced faster than it decays and, immediately after shutdown, the Xe-135 concentration starts to increase above the equilibrium concentration during reactor operation.

Eventually, all the I-135 decays and the Xenon concentration reaches a maximum concentration, shown by line CD in Fig. 3. Loss of Xenon continues to occur by decay only and the Xenon concentration falls, exponentially, from the maximum value, ie, the level in A falls from its value at CD.

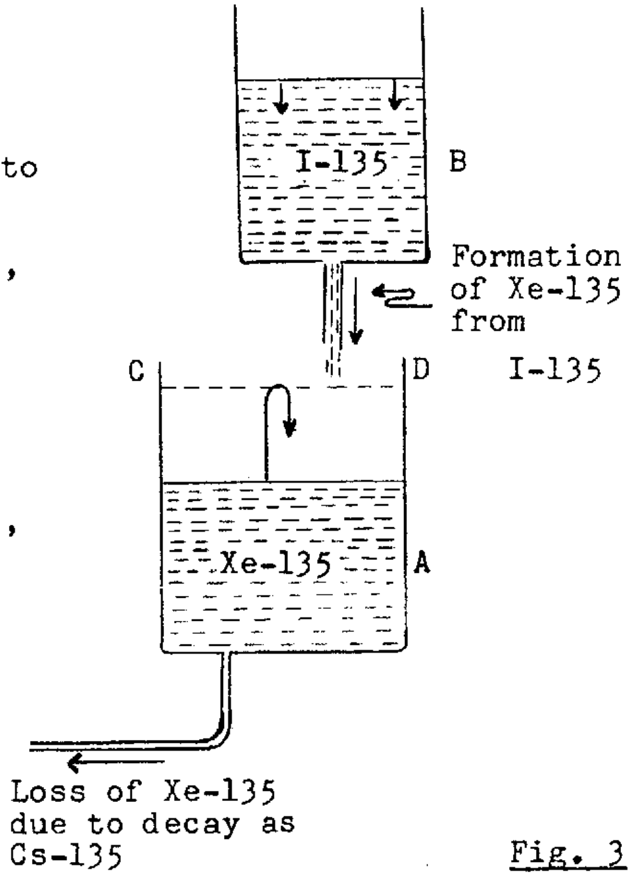

Fig. 3

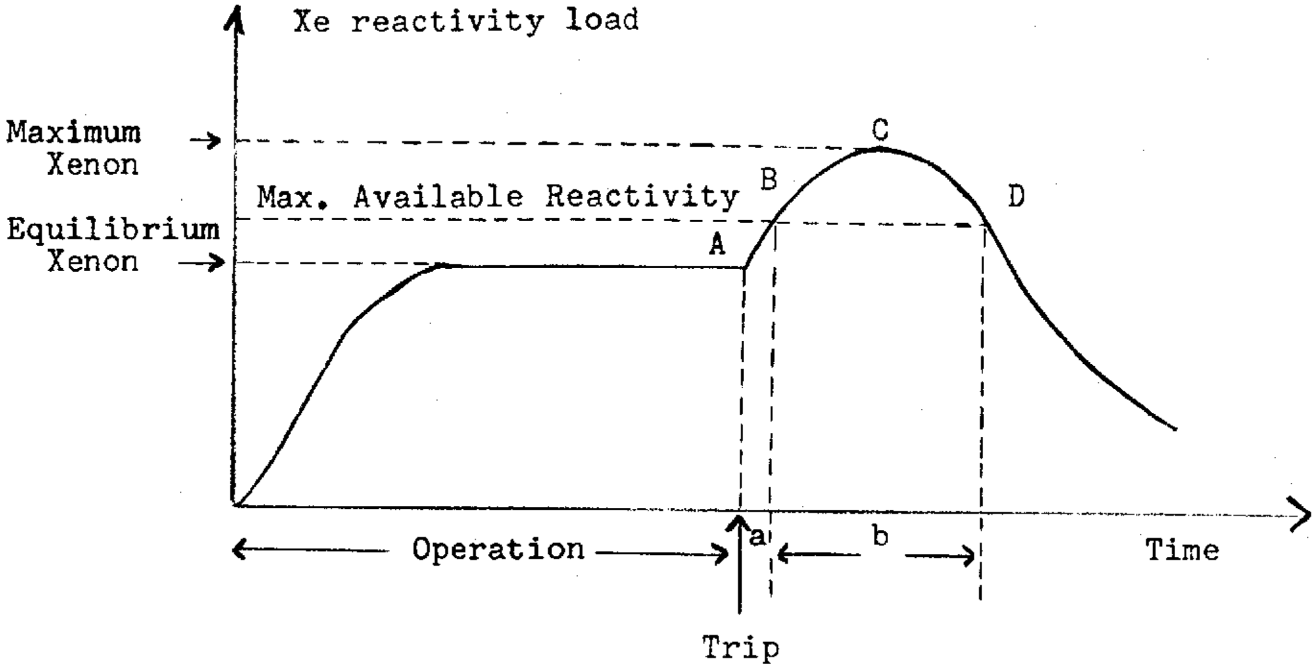

Fig. 4

Fig. 4 shows the increase of Xe-135 during reactor operation, to its equilibrium level and its increase above this equilibrium level following a reactor trip at A. The maximum Xenon concentration occurs at C. Such a build-up of Xenon, following a reactor trip, is known as the XENON TRANSIENT. The maximum or peak Xenon load depends on the power level, prior to the trip, but it may be double the equilibrium Xenon load, ie, 45 to 50 mk or higher.

Although there is enough reactivity to overcome the equilibrium load, it is not feasible to provide enough additional reactivity, in the reactor to overcome the peak load of the Xenon transient. However, sufficient reactivity may be available to overcome the Xenon load up to point B. This makes it possible to start up the reactor again between A and B, but if the reactor power is not restored, before the Xenon reaches B, then the reactor can not be started up until the Xenon comes back down to D.

The time period, 'a', during which there is enough reactivity available to overcome the Xenon poison and to make reactor start-up possible, is known as the POISON OVERRIDE TIME or the TIME TO POISON.

The time period, 'b', during which there is not enough reactivity to overcome the Xenon poison and during which the reactor cannot be started up, is known as the POISON OUT TIME or the POISON SHUTDOWN TIME.

The time periods, shown in Fig. 4, are all out of proportion. In practice, the poison override time is only 15 or 20 minutes, the time from A to the peak Xenon is about 11 hours and the poison shutdown time 24 to 30 hours.

The poison override time can be extended, up to 30 or 40 minutes by providing additional reactivity, when it is required, by inserting additional fuel, into the reactor, in the form of an enriched booster.

ASSIGNMENT

1. Why are fission products, such as Xenon-135, referred to as poisons?
2. (a) In what two ways is Xe-135 produced in the fuel?

   (b) In what two ways is Xe-135 removed?
3. What is meant by equilibrium Xenon concentration and when is this concentration in the fuel reached?
4. State two consequences of the build up of Xenon poison during reactor operation.
5. Explain the Xenon transient that occurs after a reactor trip.
6. Explain the terms "Poison override time" and "Poison shutdown time".
7. How can the poison override time be extended without increasing the core size?

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