

## Nuclear Theory - Course 127

### EFFECTS DUE TO FISSION PRODUCT ACCUMULATION

The temperature effects considered in the previous lesson are relatively short-term effects, ie, the temperature changes, and the resulting reactivity changes occur soon after the change in power occurs. Long-term effects arise due to changes occurring in the fuel as a result of fuel irradiation. These changes are:

- (a) Accumulation of fission products in the fuel, and
- (b) Burnup of U-235 and build-up of plutonium.

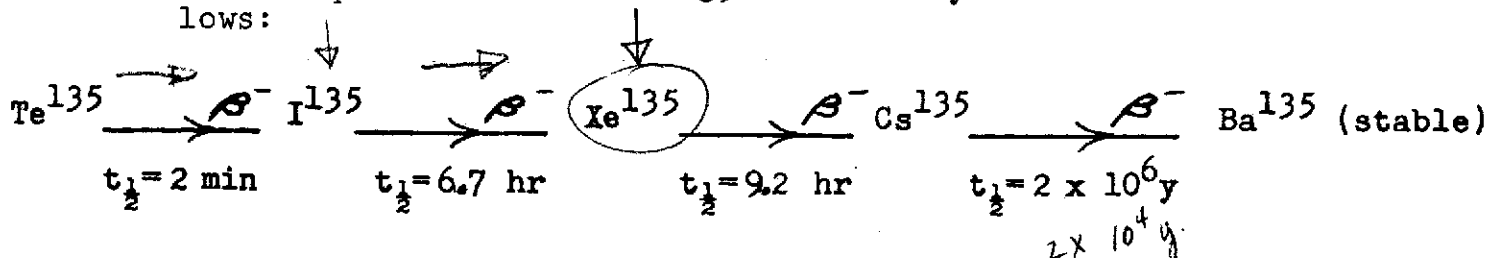
The first of these can also cause a transient change in reactivity on reactor shutdown which can affect the availability of the reactor in a base load station. The gradual and the transient change in reactivity due to (a) will be considered in this lesson.

#### The Build-up of Xenon Poison

All fission products are classified as reactor poisons because they all absorb neutrons to some extent. However, the two most important poisons by far are Xenon-135 and Samarium-149. They have very large thermal neutron capture cross sections and they, therefore, cause substantial changes in reactivity as they build up in the fuel. The one important difference between them is that Xe-135 is radioactive, whereas Sm-149 is stable. This is why they will be discussed separately.

Xenon-135 is produced in the fuel in one of two ways:

- (a) Directly as a fission product. About 5% of the total Xe-135 is produced this way.
- (b) Indirectly from the decay of Iodine-135, which in turn is produced as a fission product or from the decay of the fission product Tellurium-135. The decay chain is as follows:



Xe-135 is removed from the reactor in two ways:

- (a) By decaying to Caesium-135, as shown above, and
- (b) By capturing thermal neutrons and forming Xe-136. This Xe-136 is much less of a poison than Xe-135 and its formation can be considered as a complete removal of poison.

When the reactor is first started up, the Xe-135 is formed by the direct method only, since the I-135 has not as yet been formed. So its rate of formation is low. As the iodine concentration grows, the rate of formation of xenon increases and, since its rate of removal is still low, the xenon concentration increases more and more rapidly. However, as the xenon concentration increases its decay rate increases, and its probability of capturing neutrons increases. So, as the xenon builds up, its net rate of removal increases until eventually the rate of removal becomes equal to the rate of formation. Xe-135 is removed just as fast as it is produced and from then on its concentration remains constant. This final constant concentration is known as the equilibrium xenon concentration. The growth of xenon, up to its equilibrium concentration, is shown graphically by the portion AB of Fig. 1.

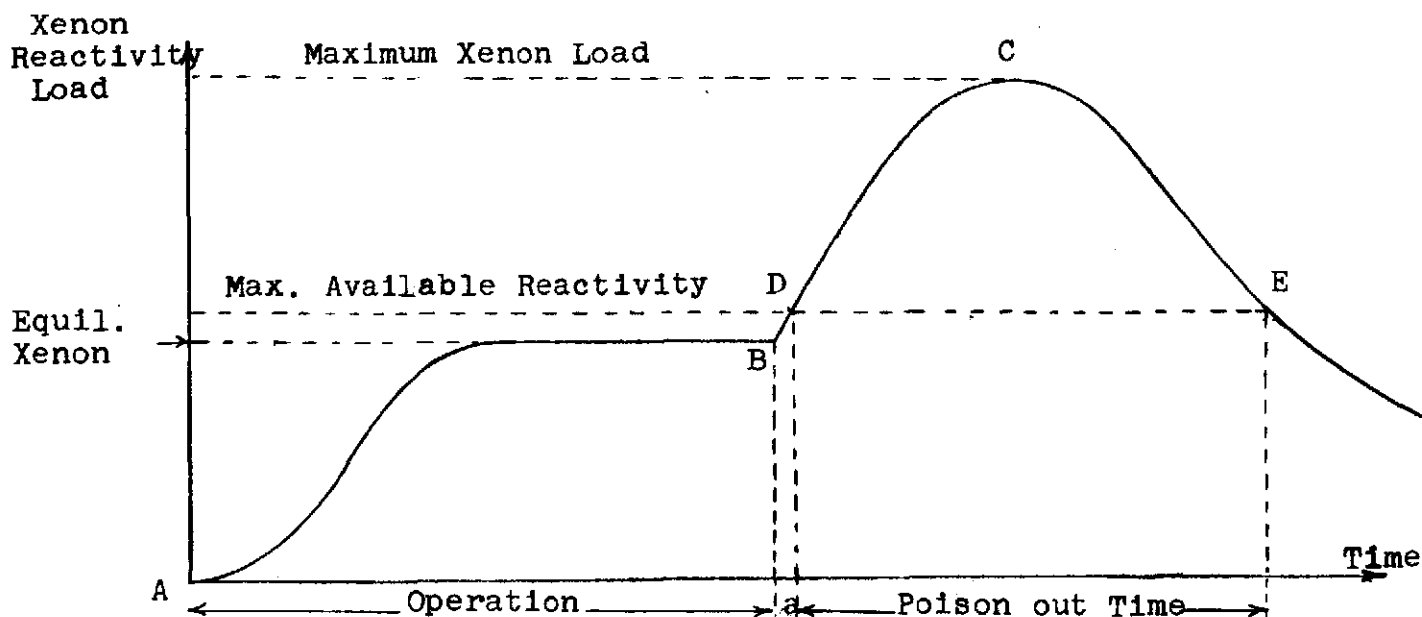


Fig. 1

The slow initial rate of growth of the Xe-135 is very exaggerated in Fig. 1. The actual xenon curve for NPD is shown in Fig. 2. The initial slow rate of growth is due to the fact that the xenon is only being produced directly as a fission product because the I-135 has not as yet been produced.

It may be seen from Fig. 2 that it takes 60 to 70 hours for the xenon concentration to reach its equilibrium value but that it is up to 90% of the equilibrium value for a particular power level in about 25 hours of reactor operation at this power.

The POISONING,  $P$ , due to the absorption of thermal neutrons by Xe-135, is defined as the ratio of the number of thermal neutrons absorbed by Xe-135 to the number absorbed in fissionable material.

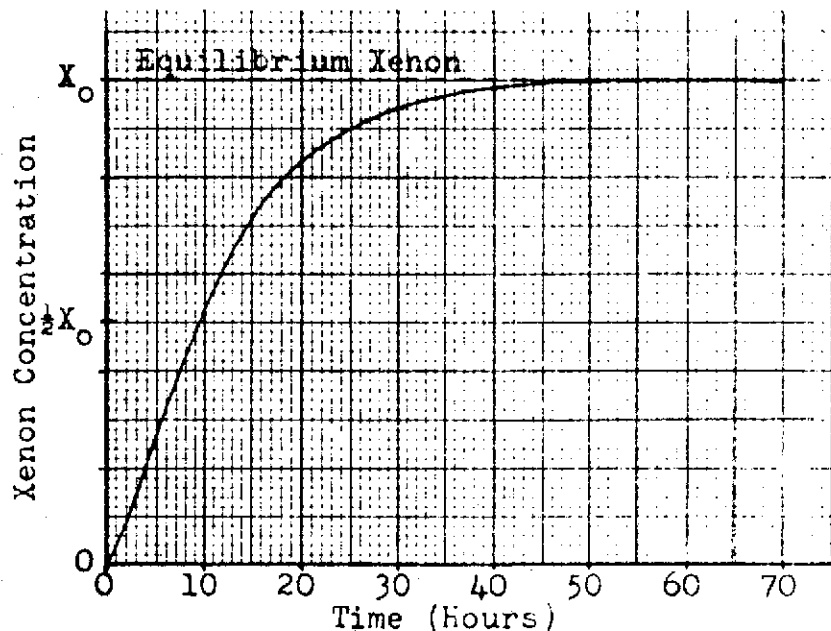


Fig. 2

The equilibrium poison,  $P_0$ , for natural uranium fuel, is given by:

$$P_0 = \frac{1.04 \times 10^{-19} \phi}{(2.1 \times 10^{-5}) + (3 \times 10^{-18} \phi)}$$

where  $\phi$  is the thermal neutron flux.

Therefore, for a particular reactor, the poisoning,  $P_0$ , depends only on the operating flux,  $\phi$ . The variation of  $P_0$  with  $\phi$  in a natural uranium reactor is shown in Fig. 3. The graph shows that, if the flux is less than  $10^{12}$  n/cm<sup>2</sup>/sec, the poisoning is small. There is, then, a rapid increase in  $P_0$  up to  $\phi = 10^{14}$  n/cm<sup>2</sup>/sec, after which the rate of increase slows down.  $P_0$  eventually reaches a limiting value of about 0.035.

Because Xe-135 absorbs neutrons, which could otherwise be used for fission, there is a reduction in reactivity due to the growth of xenon. This reduction in reactivity is known as the XENON REACTIVITY LOAD. Enough reactivity must be built into the reactor in order that the regulating system can compensate for the loss of reactivity as the xenon concentration increases. The reactor must, therefore, be bigger than the critical size required with fresh fuel. However, when the reactor is first started up, the xenon concentration is either zero or very small.

Thus, if moderator level reactivity control only is used, as at NPD, the moderator level would be well below its normal operating level. This results in a reduction in the permissible power and a loss of energy revenue. In Douglas Point and Pickering, boric acid is used as a neutron absorber or poison in the moderator to enable the reactor to operate at full tank and, therefore, at full power even when the xenon load is low. As the xenon grows, the boric acid is removed with ion exchange columns.

The growth of xenon load to equilibrium is, of course, identical to that of the xenon concentration and it is the growth of the xenon load that is shown in Fig. 1.

The xenon load varies with the flux in the same way as the poisoning, shown in Fig. 3.

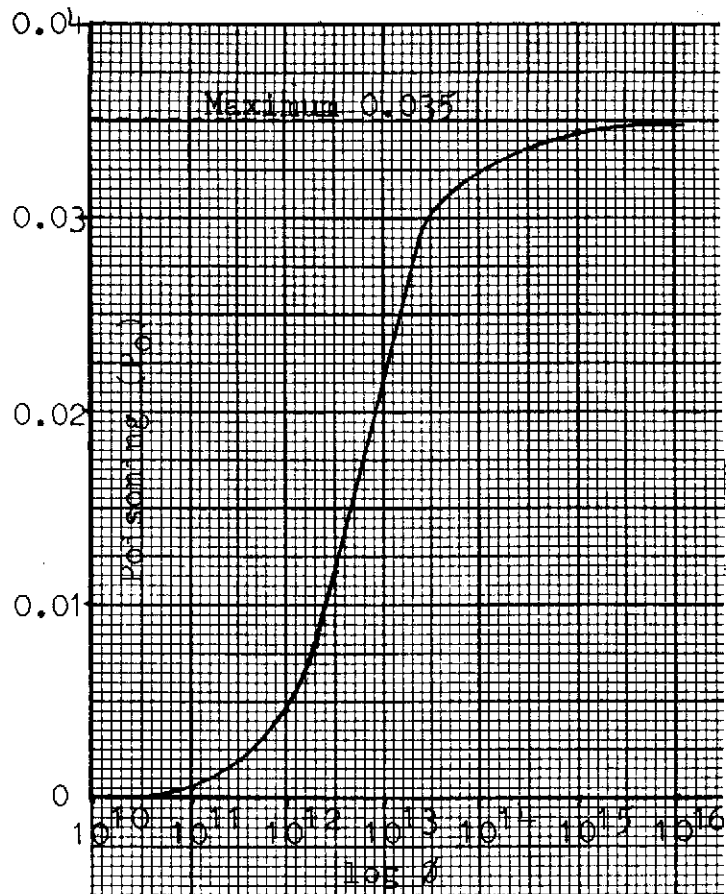


Fig. 3

#### Xenon Build-up During Reactor Shutdown

An important aspect of poisoning arises on reactor shutdown. Suppose the reactor trips, or is shut down, at the point B in Fig. 1. The neutron flux decreases to a low value and the direct production of I-135 and Xe-135 as fission products cease. However, the I-135 already present in the fuel continues to decay to Xe-135 and so the formation of xenon continues at a rate a little lower than at reactor power.

Removal of Xe-135 by neutron absorption stops, whereas its removal by decay continues at the same rate as before. The net result is that the rate of production is now greater than the rate of removal and the Xe-135 concentration and reactivity load starts to increase along the portion BC of the curve in Fig. 1.

However, as the Xe-135 concentration increases, its rate of decay increases. Also its rate of formation decreases because

of the decrease in the amount of I-135 remaining. Eventually, the rate of removal becomes equal to the rate of formation and then becomes greater than the rate of formation. The net result is that, as shown in Fig. 1, the xenon load reaches a maximum value at C, and then starts to decrease, eventually decaying exponentially with the Xe-135 half-life. Such a build-up of xenon is known as the Xenon Transient. The maximum xenon concentration occurs about 9 to 11 hours after the trip. The maximum xenon load may well be double the equilibrium load and could reach a much higher value.

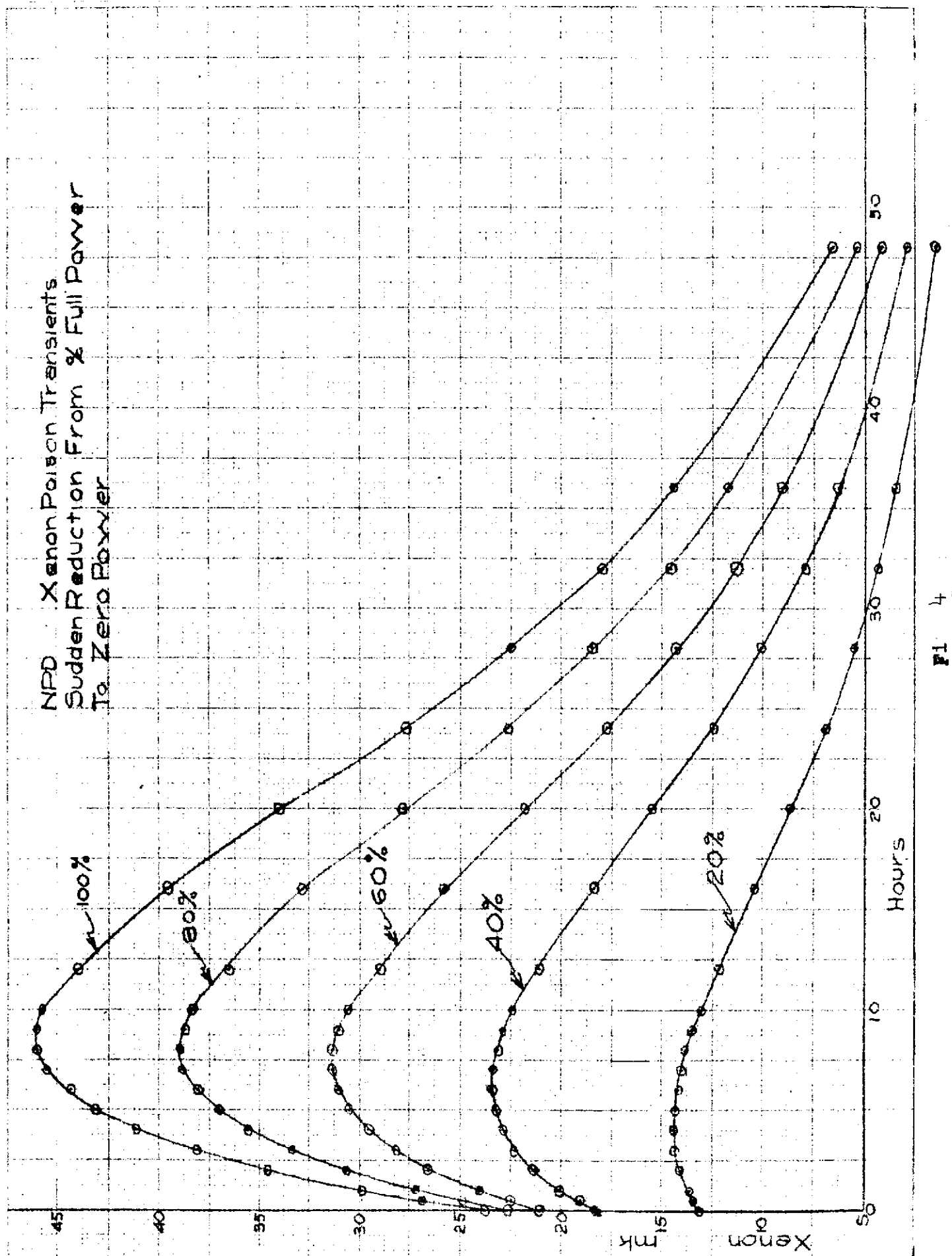
The maximum xenon reactivity load depends on the thermal neutron flux, or the power, at the time of the trip. Fig. 4 shows how the xenon transient varies when a reactor is shut down from different percentages of full power. It should also be noted that the transient continues to increase beyond flux values of  $10^{14}$  n/cm<sup>2</sup>/sec and does not level out in the manner of the equilibrium load.

The initial rate of rise of the xenon load, after a reactor shutdown, is also proportional to average flux or power at the time of the shutdown.

If the reactivity built into the core is only just enough to overcome the equilibrium xenon load, then it may well be 24 to 30 hours before the xenon decays sufficiently to enable the reactor to be started up again. It is not feasible to provide enough excess reactivity to overcome the peak xenon but sufficient reactivity may be provided to make it possible to start up within half or three-quarters of an hour of a trip, ie, from B to D in Fig. 1. The time period "a", during which enough reactivity is available to overcome the xenon load and start up the reactor, is known as the POISON OVERRIDE TIME or the TIME TO POISON. The time from D to E, during which the reactor cannot be started up because there is not enough reactivity to overcome the xenon load, is known as the POISON-OUT TIME.

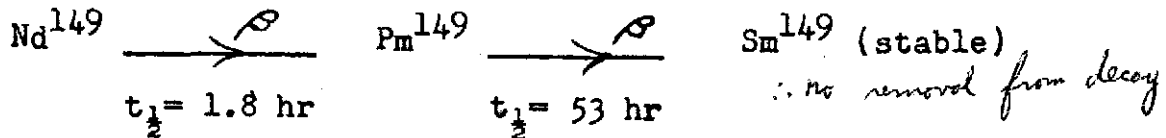
In a reactor with a negative moderator temperature coefficient, some of the required additional reactivity can be obtained by cooling the moderator. However, the best method of providing this reactivity is to insert extra fuel, in the form of a booster rod, into the reactor. This avoids increasing the fuel inventory in the core since the booster rod is only used when required.

The poison override time can be extended by a schedule of power reductions, provided that prior warning is given of the intended shutdown. Some loss of energy production is sustained but poisoning out, with its associated greater production loss, is avoided.



### The Build-up of Samarium Poison

Of the stable poisons, the most notable is Samarium-149, which is formed by the decay of Promethium-149, which in turn is formed by the decay of Neodymium-149:



Sm-149 poison reaches its equilibrium in much the same way as Xe-135, as shown in the portion AB of the graph in Fig. 5. Sm-149, being stable, is not removed by decay and its rate of removal by neutron capture is slower than that of xenon. However, its rate of formation is also smaller, with the result that it reaches equilibrium more slowly than xenon. The Sm-149 equilibrium load is only slightly greater than a fifth of that of Xe-135.

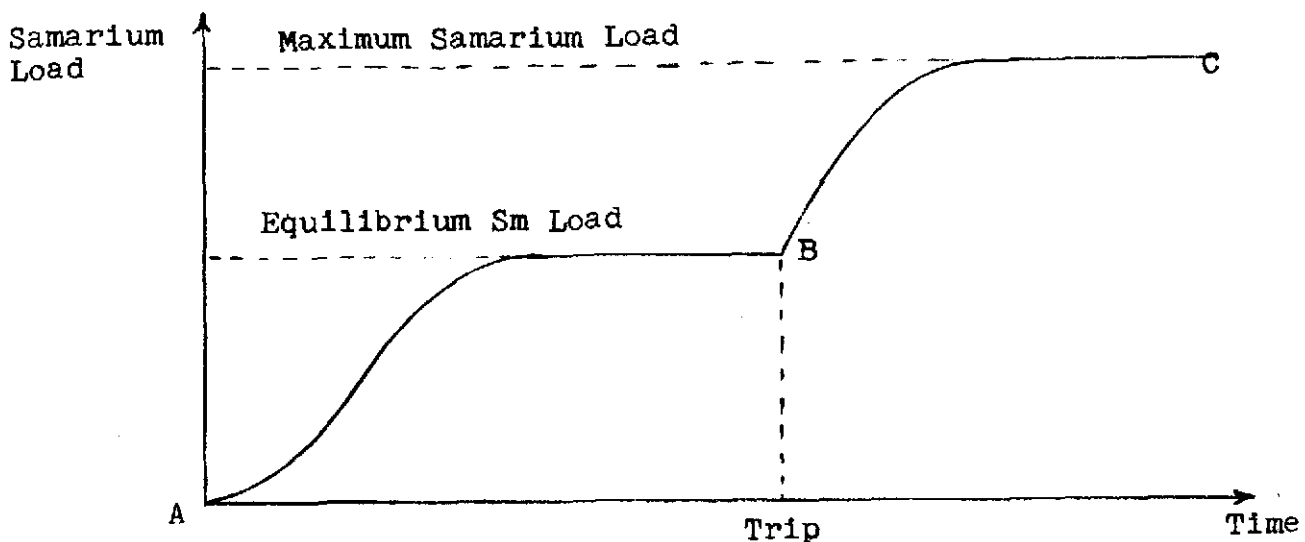
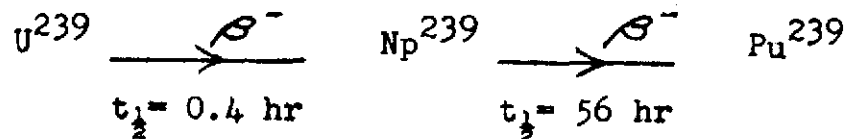


Fig. 5

When the reactor trips, or is shut down, the samarium increases much in the same way as the xenon. However, since there is no Sm-149 decay, it continues to increase to a new equilibrium level, until all the Pm-149 has decayed. The growth of Sm-149, after a trip, is shown in the portion BC of Fig. 5. The maximum Sm-149 load will be two or three times the equilibrium operating load.

The value of the equilibrium samarium load is independent of the operating flux but the maximum transient load does depend on the flux or power at the time of the shutdown.

Note that the only way to reduce the Sm-149 is to start up the reactor and remove Sm-149 by neutron capture. An allowance in the design of the reactor core must be made for the equilibrium Sm-149 load. However, the transient following shutdown is normally no problem since it is balanced by the Pu-239 transient. It was previously shown that, as a result of neutron capture in U-238, Pu-239 is formed by the following decay chain.



The decay of Np-239 takes place at approximately the same rate as decay of Pm-149 and it happens that the enrichment effect of the extra Pu-239 formed after shutdown almost balances the load due to Sm-149.

Following startup there is a slight overall enrichment effect, since the Sm-149 returns to equilibrium more quickly than the Pu-239. This effect is normally masked out by xenon build-up and is not obvious.

#### ASSIGNMENT

1. (a) Explain briefly why xenon concentration increases to an equilibrium value during reactor operation.
- (b) What is meant by "Equilibrium Xenon Reactivity Load"?
- (c) On what does this xenon load depend?
2. Explain why there is a transient increase in xenon concentration after reactor shutdown and how the increase depends on the operating power prior to shutdown.
3. (a) Explain the terms "Poison Override Time" and "Poison-Out Time".
- (b) What is the significance of using a booster rod in a reactor?



4. (a) Why does samarium build-up, following a shutdown, differ from that of xenon?
- (b) How can the samarium load, in a reactor, be reduced?
- (c) Why is it necessary to make allowance in the design of a reactor for the equilibrium samarium load but not for the transient samarium load?

A. Williams

<u>Poisons</u>	<u><math>\sigma_a</math> (barns)</u>	<u><math>t_{1/2}</math></u>
Xe <sup>135</sup>	2,700,000	
Sm <sup>149</sup>	65,000	
Sm <sup>151</sup>	14,800	
Cd <sup>113</sup>	19,740	
Eu <sup>155</sup>	13,600	
Gd <sup>155</sup>	255,000	