
XENON

Xenon-135 has a tremendous impact on the operation of a nuclear reactor. It is important to understand the mechanisms that produce and remove xenon from the reactor to predict how the reactor will respond following changes in power level.

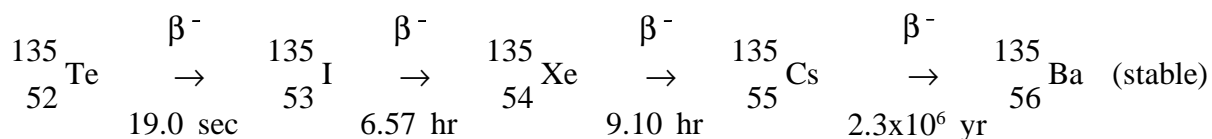
- EO 4.1** LIST two methods of production and two methods of removal for xenon-135 during reactor operation.
- EO 4.2** STATE the equation for equilibrium xenon-135 concentration.
- EO 4.3** DESCRIBE how equilibrium xenon-135 concentration varies with reactor power level.
- EO 4.4** DESCRIBE the causes and effects of a xenon oscillation.
- EO 4.5** DESCRIBE how xenon-135 concentration changes following a reactor shutdown from steady-state conditions.
- EO 4.6** EXPLAIN the effect that pre-shutdown power levels have on the xenon-135 concentration after shutdown.
- EO 4.7** STATE the approximate time following a reactor shutdown at which the reactor can be considered "xenon free."
- EO 4.8** EXPLAIN what is meant by the following terms:
- a. Xenon precluded startup
 - b. Xenon dead time
- EO 4.9** DESCRIBE how xenon-135 concentration changes following an increase or a decrease in the power level of a reactor.
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Fission Product Poisons

Fission fragments generated at the time of fission decay to produce a variety of fission products. Fission products are of concern in reactors primarily because they become parasitic absorbers of neutrons and result in long term sources of heat. Although several fission products have significant neutron absorption cross sections, xenon-135 and samarium-149 have the most substantial impact on reactor design and operation. Because these two fission product poisons remove neutrons from the reactor, they will have an impact on the thermal utilization factor and thus k_{eff} and reactivity.

Production and Removal of Xenon-135

Xenon-135 has a 2.6×10^6 barns neutron absorption cross section. It is produced directly by some fissions, but is more commonly a product of the tellurium-135 decay chain shown below. The fission yield (γ) for xenon-135 is about 0.3%, while γ for tellurium-135 is about 6%.



The half-life for tellurium-135 is so short compared to the other half-lives that it can be assumed that iodine-135 is produced directly from fission. Iodine-135 is not a strong neutron absorber, but decays to form the neutron poison xenon-135. Ninety-five percent of all the xenon-135 produced comes from the decay of iodine-135. Therefore, the half-life of iodine-135 plays an important role in the amount of xenon-135 present.

The rate of change of iodine concentration is equal to the rate of production minus the rate of removal. This can be expressed in the equation below.

rate of change of iodine concentration = yield from fission - decay rate - burnup rate
or

$$\frac{dN_I}{dt} = \gamma_I \Sigma_f^{\text{fuel}} \phi - \lambda_I N_I - \sigma_a^J N_I \phi$$

where:

$$\begin{array}{ll}
 N_I & = \text{}^{135}\text{I concentration} \\
 \gamma_I & = \text{fission yield of } {}^{135}\text{I} \\
 \Sigma_f^{\text{fuel}} & = \text{macroscopic fission cross section fuel} \\
 \phi & = \text{thermal neutron flux} \\
 \lambda_I & = \text{decay constant for } {}^{135}\text{I} \\
 \sigma_a^J & = \text{microscopic absorption cross section } {}^{135}\text{I}
 \end{array}$$

Since the σ_a^J is very small, the burn up rate term may be ignored, and the expression for the rate of change of iodine concentration is modified as shown below.

$$\frac{dN_I}{dt} = \gamma_I \Sigma_f^{\text{fuel}} \phi - \lambda_I N_I$$

When the rate of production of iodine equals the rate of removal of iodine, equilibrium exists. The iodine concentration remains constant and is designated $N_I(\text{eq})$. The following equation for the equilibrium concentration of iodine can be determined from the preceding equation by setting the two terms equal to each other and solving for $N_I(\text{eq})$.

$$N_I(\text{eq}) = \frac{\gamma_I \Sigma_f^{\text{fuel}} \phi}{\lambda_I}$$

Since the equilibrium iodine concentration is proportional to the fission reaction rate, it is also proportional to reactor power level.

The rate of change of the xenon concentration is equal to the rate of production minus the rate of removal. Recall that 5% of xenon comes directly from fission and 95% comes from the decay of iodine. The rate of change of xenon concentration is expressed by the following equations.

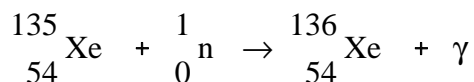
$$\text{rate of change of xenon-135 concentration} = \left(\text{xenon-135 yield from fission} \right) + \left(\text{iodine-135 decay} \right) - \left(\text{xenon-135 decay} \right) - \left(\text{xenon-135 burnup} \right)$$

$$\frac{dN_{\text{Xe}}}{dt} = \gamma_{\text{Xe}} \Sigma_f^{\text{fuel}} \phi + \lambda_I N_I - \lambda_{\text{Xe}} N_{\text{Xe}} - \sigma_a^{\text{Xe}} N_{\text{Xe}} \phi$$

where:

$$\begin{aligned} N_{\text{Xe}} &= {}^{135}\text{Xe concentration} \\ \gamma_{\text{Xe}} &= \text{fission yield of } {}^{135}\text{Xe} \\ \Sigma_f^{\text{fuel}} &= \text{macroscopic fission cross section of the fuel} \\ \phi &= \text{thermal neutron flux} \\ \lambda_I &= \text{decay constant for } {}^{135}\text{I} \\ N_I &= {}^{135}\text{I concentration} \\ \lambda_{\text{Xe}} &= \text{decay constant for } {}^{135}\text{Xe} \\ \sigma_a^{\text{Xe}} &= \text{microscopic absorption cross section } {}^{135}\text{Xe} \end{aligned}$$

The xenon burnup term above refers to neutron absorption by xenon-135 by the following reaction.



Xenon-136 is not a significant neutron absorber; therefore, the neutron absorption by xenon-135 constitutes removal of poison from the reactor. The burnup rate of xenon-135 is dependent upon the neutron flux and the xenon-135 concentration.

The equilibrium concentration of xenon-135 is designated $N_{\text{Xe}}(\text{eq})$, and is represented as shown below.

$$N_{\text{Xe}}(\text{eq}) = \frac{\gamma_{\text{Xe}} \Sigma_f^{\text{fuel}} \phi + \lambda_I N_I}{\lambda_{\text{Xe}} + \sigma_a^{\text{Xe}} \phi}$$

For xenon-135 to be in equilibrium, iodine-135 must also be in equilibrium. Substituting the expression for equilibrium iodine-135 concentration into the equation for equilibrium xenon results in the following.

$$N_{Xe} \text{ (eq)} = \frac{(\gamma_{Xe} + \gamma_I) \sum_f^{fuel} \phi}{\lambda_{Xe} + \sigma_a^{Xe} \phi}$$

From this equation it can be seen that the equilibrium value for xenon-135 increases as power increases, because the numerator is proportional to the fission reaction rate. Thermal flux is also in the denominator; therefore, as the thermal flux exceeds 10^{12} neutrons/cm²-sec, the $\sigma_a^{Xe} \phi$ term begins to dominate, and at approximately 10^{15} neutrons/cm²-sec, the xenon-135 concentration approaches a limiting value. The equilibrium iodine-135 and xenon-135 concentrations as a function of neutron flux are illustrated in Figure 4.

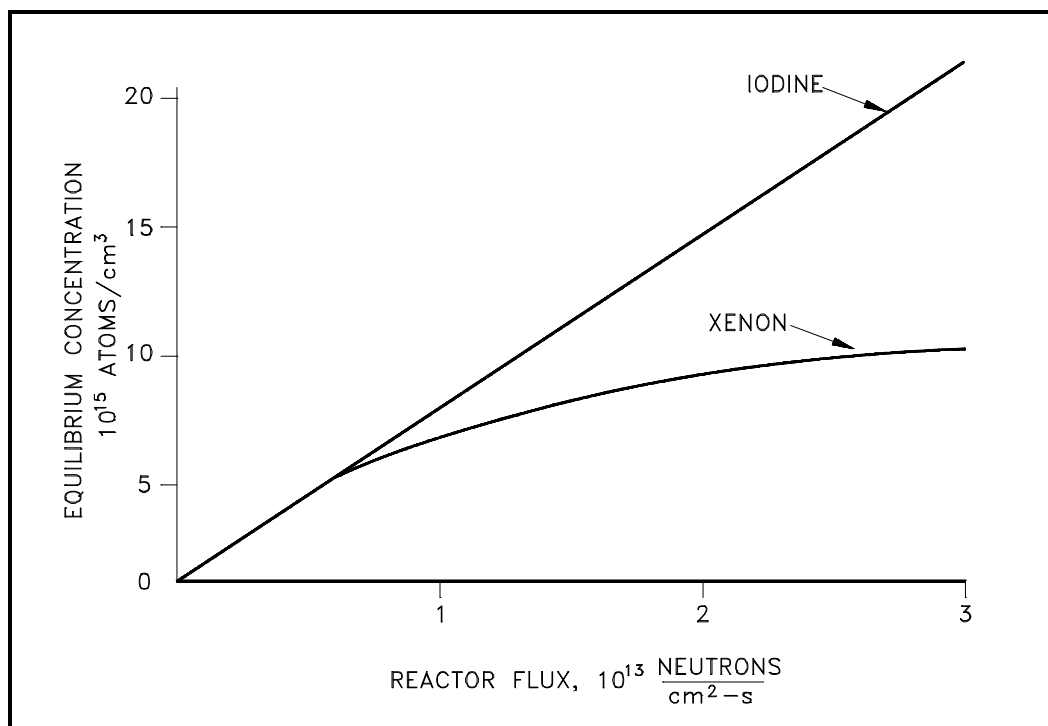


Figure 4 Equilibrium Iodine-135 and Xenon-135 Concentrations Versus Neutron Flux

The higher the power level, or flux, the higher the equilibrium xenon-135 concentration, but equilibrium xenon-135 is not directly proportional to power level. For example, equilibrium xenon-135 at 25% power is more than half the value for equilibrium xenon-135 at 100% power for many reactors. Because the xenon-135 concentration directly affects the reactivity level in the reactor core, the negative reactivity due to the xenon concentrations for different power levels or conditions are frequently plotted instead of the xenon concentration.

Xenon-135 Response to Reactor Shutdown

When a reactor is shutdown, the neutron flux is reduced essentially to zero. Therefore, after shutdown, xenon-135 is no longer produced by fission and is no longer removed by burnup. The only remaining production mechanism is the decay of the iodine-135 which was in the core at the time of shutdown. The only removal mechanism for xenon-135 is decay.

$$\frac{dN_{Xe}}{dt} = \lambda_I N_I - \lambda_{Xe} N_{Xe}$$

Because the decay rate of iodine-135 is faster than the decay rate of xenon-135, the xenon concentration builds to a peak. The peak is reached when the product of the terms $\lambda_I N_I$ is equal to $\lambda_{Xe} N_{Xe}$ (in about 10 to 11 hours). Subsequently, the production from iodine decay is less than the removal of xenon by decay, and the concentration of xenon-135 decreases. The greater the flux level prior to shutdown, the greater the concentration of iodine-135 at shutdown; therefore, the greater the peak in xenon-135 concentration after shutdown. This phenomenon can be seen in Figure 5, which illustrates the negative reactivity value of xenon-135 following shutdown from various neutron flux levels.

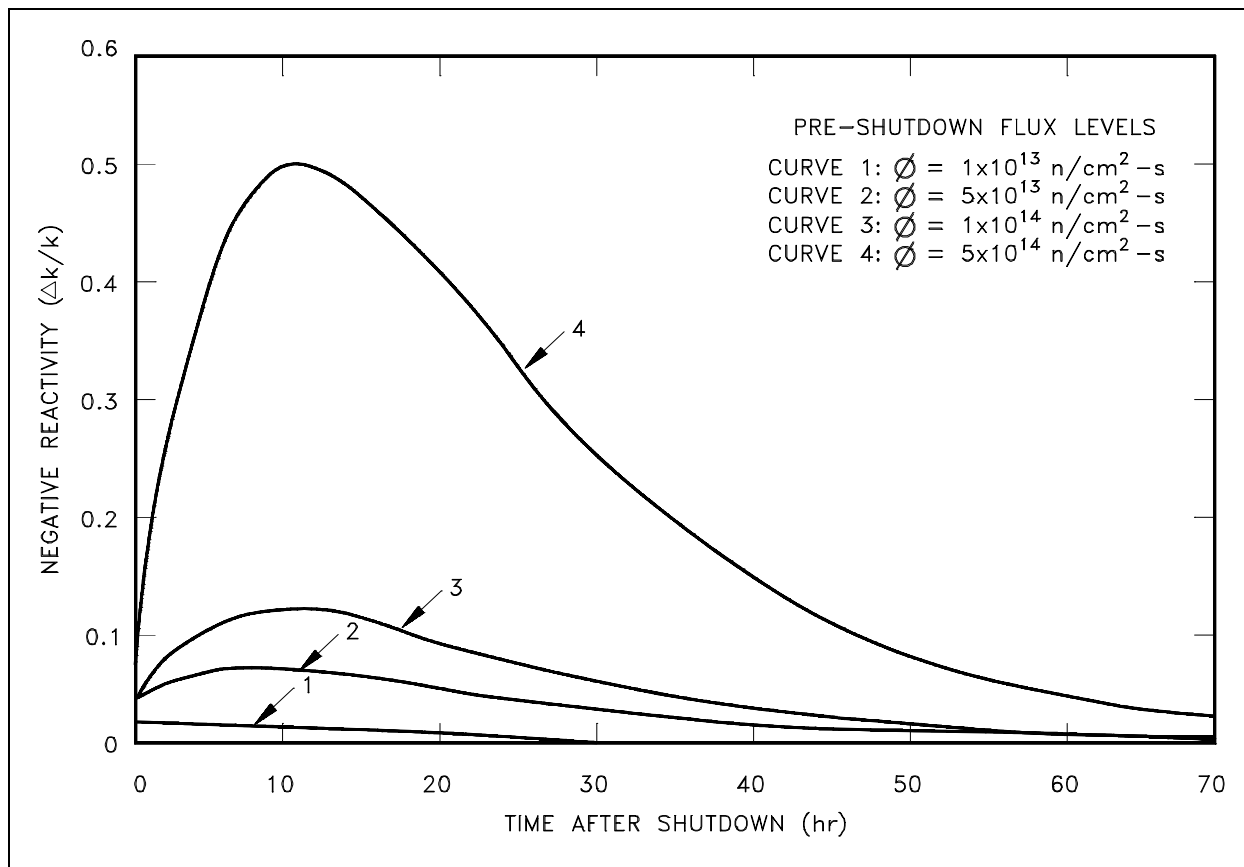


Figure 5 Xenon-135 Reactivity After Reactor Shutdown

Negative xenon reactivity, also called xenon poisoning, may provide sufficient negative reactivity to make the reactor inoperable because there is insufficient positive reactivity available from control rod removal or chemical shim dilution (if used) to counteract it. The inability of the reactor to be started due to the effects of xenon is sometimes referred to as a *xenon precluded startup*. The period of time where the reactor is unable to "override" the effects of xenon is called *xenon dead time*. Because the amount of excess core reactivity available to override the negative reactivity of the xenon is usually less than 10% $\Delta k/k$, thermal power reactors are normally limited to flux levels of about 5×10^{13} neutrons/cm²-sec so that timely restart can be ensured after shutdown. For reactors with very low thermal flux levels ($\sim 5 \times 10^{12}$ neutrons/cm²-sec or less), most xenon is removed by decay as opposed to neutron absorption. For these cases, reactor shutdown does not cause any xenon-135 peaking effect.

Following the peak in xenon-135 concentration about 10 hours after shutdown, the xenon-135 concentration will decrease at a rate controlled by the decay of iodine-135 into xenon-135 and the decay rate of xenon-135. For some reactors, the xenon-135 concentration about 20 hours after shutdown from full power will be the same as the equilibrium xenon-135 concentration at full power. About 3 days after shutdown, the xenon-135 concentration will have decreased to a small percentage of its pre-shutdown level, and the reactor can be assumed to be xenon free without a significant error introduced into reactivity calculations.

Xenon-135 Oscillations

Large thermal reactors with little flux coupling between regions may experience spatial power oscillations because of the non-uniform presence of xenon-135. The mechanism is described in the following four steps.

- (1) An initial lack of symmetry in the core power distribution (for example, individual control rod movement or misalignment) causes an imbalance in fission rates within the reactor core, and therefore, in the iodine-135 buildup and the xenon-135 absorption.
- (2) In the high-flux region, xenon-135 burnout allows the flux to increase further, while in the low-flux region, the increase in xenon-135 causes a further reduction in flux. The iodine concentration increases where the flux is high and decreases where the flux is low.
- (3) As soon as the iodine-135 levels build up sufficiently, decay to xenon reverses the initial situation. Flux decreases in this area, and the former low-flux region increases in power.
- (4) Repetition of these patterns can lead to xenon oscillations moving about the core with periods on the order of about 15 hours.

With little change in overall power level, these oscillations can change the local power levels by a factor of three or more. In a reactor system with strongly negative temperature coefficients, the xenon-135 oscillations are damped quite readily. This is one reason for designing reactors to have negative moderator-temperature coefficients.

Xenon-135 Response to Reactor Power Changes

During periods of steady state operation, at a constant neutron flux level, the xenon-135 concentration builds up to its equilibrium value for that reactor power in about 40 to 50 hours. Figure 6 illustrates a typical xenon transient that occurs as a result of a change in reactor power level. At time zero, reactor power is raised from 50% power to 100% power. When the reactor power is increased, xenon concentration initially decreases because the burnup is increased at the new higher power level. Because 95% of the xenon production is from iodine-135 decay, which has a 6 to 7 hour half-life, the production of xenon remains constant for several hours. After a few hours (roughly 4 to 6 hours depending on power levels) the rate of production of xenon from iodine and fission equals the rate of removal of xenon by burnup and decay. At this point, the xenon concentration reaches a minimum. The xenon concentration then increases to the new equilibrium level for the new power level in roughly 40 to 50 hours. It should be noted that the magnitude and the rate of change of xenon concentration during the initial 4 to 6 hours following the power change is dependent upon the initial power level and on the amount of change in power level. The xenon concentration change is greater for a larger change in power level.

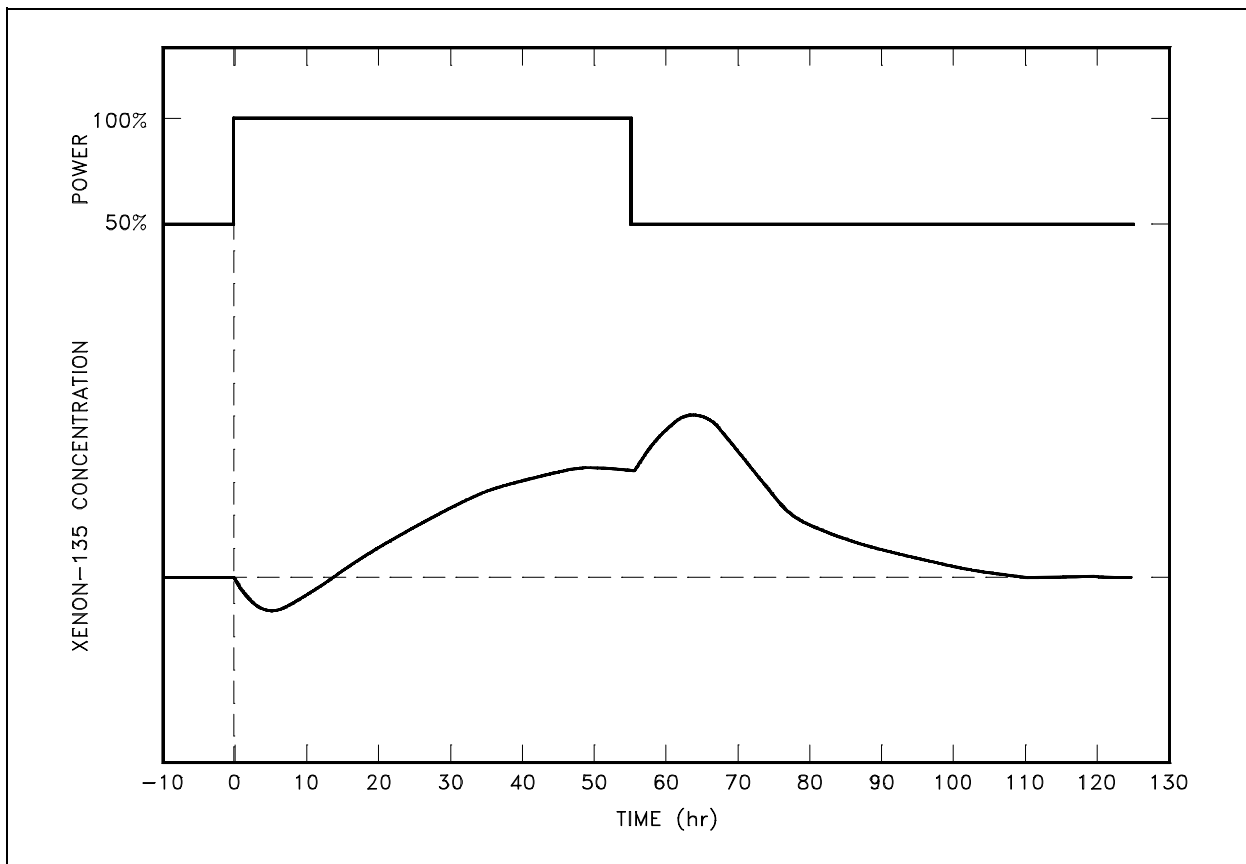


Figure 6 Xenon-135 Variations During Power Changes

When reactor power is decreased from 100% to 50% power ($t = 55$ hours), the process is reversed. There is an immediate decrease in xenon burnup, which results in an increase in xenon-135 concentration. The iodine-135 concentration is still at the higher equilibrium level for 100% power and is therefore still producing xenon-135 at the higher rate. The xenon-135 concentration continues to rise until the rate of production of xenon-135 becomes equal to the rate of removal (roughly 7 to 8 hours after the initial reduction in power level). The xenon-135 concentration then gradually decreases to the new equilibrium level in about 50 to 60 hours. The magnitude of the xenon peak is greatest if the initial power level is very high.

Maximum peak xenon occurs when a reactor that is operating at 100% equilibrium xenon concentration is suddenly shut down. The most rapid possible burnout of xenon occurs when a reactor is started up and operated at full power while this maximum peak xenon condition exists.

Summary

The important information in this chapter is summarized below.

Xenon Summary

- Xenon-135 is produced directly as a fission product and by the decay of iodine-135 during reactor operation. Xenon-135 is removed from the core by radioactive decay and by neutron absorption during reactor operation.
- The equilibrium concentration for xenon-135 is determined by the following equation.

$$N_{Xe} \text{ (eq)} = \frac{\gamma_{Xe} \Sigma_f^{\text{fuel}} \phi + \lambda_I N_I}{\lambda_{Xe} + \sigma_a^{Xe} \phi} \quad \text{or} \quad N_{Xe} \text{ (eq)} = \frac{(\gamma_{Xe} + \gamma_I) \Sigma_f^{\text{fuel}} \phi}{\lambda_{Xe} + \sigma_a^{Xe} \phi}$$

- The xenon-135 concentration increases with increasing power level in a non-linear manner. Equilibrium xenon-135 concentration reaches a maximum at a flux of about 10^{15} neutrons/cm²-sec.
- After a power increase, xenon-135 concentration will initially decrease due to the increased removal by burnout. Xenon-135 will reach a minimum about 5 hours after the power increase and then increase to a new, higher equilibrium value as the production from iodine decay increases.

Xenon Summary (Cont.)

- A xenon-135 oscillation may be caused by a rapid perturbation in the core power distribution. The xenon-135 oscillation can change local power levels in the core by a factor of three or more.
- Following a reactor shutdown, xenon-135 concentration will increase due to the decay of the iodine inventory of the core. Xenon-135 will peak approximately 10 hours after the shutdown (from 100%) and then decrease as xenon-135 decay becomes greater than the iodine-135 decay.
- The greater the pre-shutdown power level, the greater the peak value of xenon.
- The core can be considered xenon-free about 3 days after shutdown.
- A xenon precluded startup occurs when there is insufficient reactivity in the control rods to overcome the negative reactivity of xenon-135.
- Xenon dead time is the period of time where the reactor is unable to override the effects of xenon.
- After a power decrease, xenon-135 concentration will initially increase due to production by iodine decay being greater than the burnout. Xenon-135 will reach a maximum about 8 hours after the power decrease and then decrease to a new, lower equilibrium value.