CHAPTER 3: ELEMENTARY PHYSICS OF REACTOR CONTROL

MODULE D: FISSION PRODUCT POISONING

MODULE OBJECTIVES:

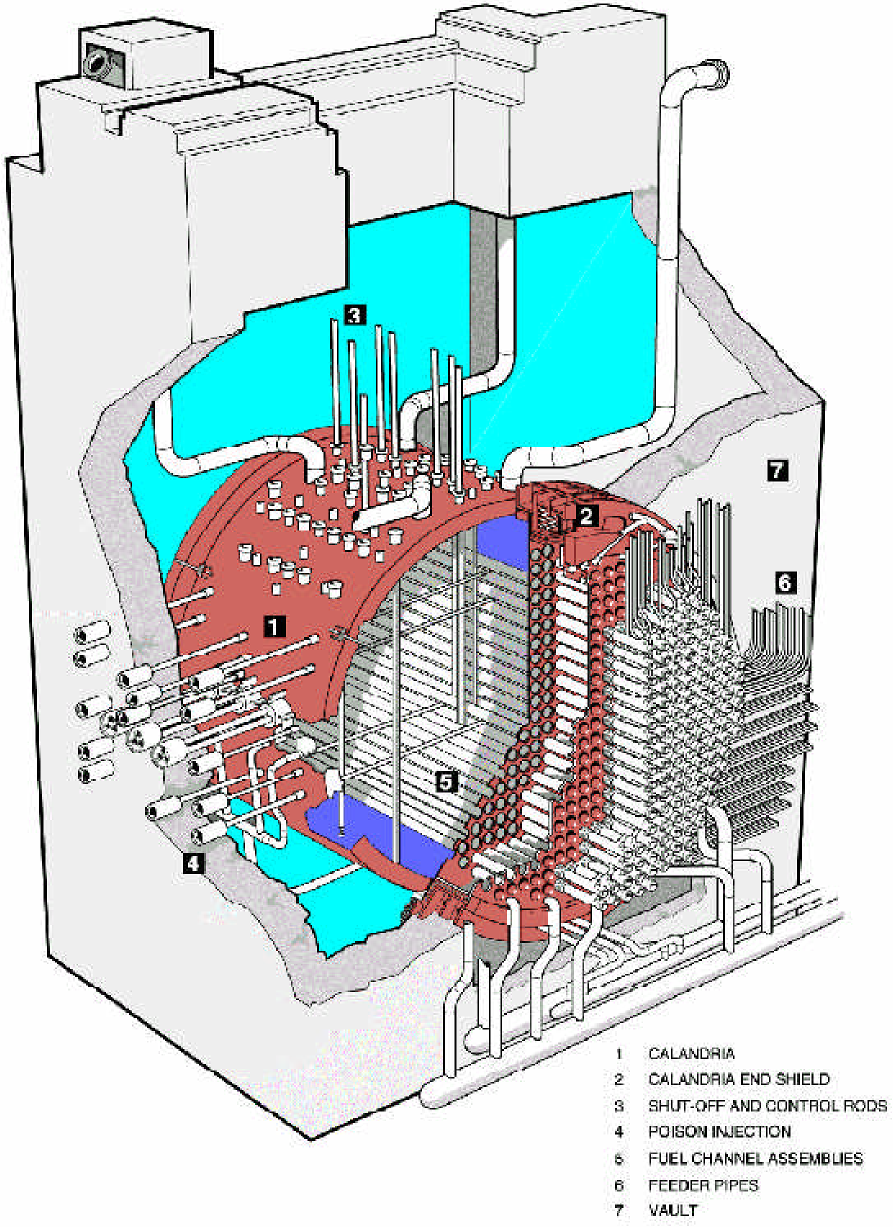
At the end of this module, you will be able to describe:

1. **the reactivity effects of fission product poisons**
2. **Xenon reactivity buildup**
3. **the production and loss rates for Iodine and Xenon**
4. **the water tank analogy for Xenon production and removal**
5. **the build-up of Iodine and Xenon to equilibrium concentrations**
6. **the steady state effects of Xenon reactivity**
7. **Xenon transient effects, including:**
   - **(a) response to reactor trip and power level reduction**
   - **(b) poison out**
   - **(c) poison override**
   - **(d) response to a power level increase**

(8) the terminology used for Xenon reactivity transient effects

1. INTRODUCTION

- **note that temperature and void effects, as discussed in the previous module, are relatively fast acting, while fission product poisoning has a much slower impact on reactivity**
- **the effects of most fission products develop with the burning of the fuel, and contribute to the need to replace the fuel at the appropriate intervals**
- **there are two fission products of particular importance to reactor design and operations, namely Xenon-135 and Samarium-149**
- **both of these fission products have very large absorption cross-sections, and cause significant reactivity changes in relatively short times**
- **while the steady state reactivity loads due to these fission product 'poisons' can be readily accommodated in the design and operation of the reactor, the large and rapid build-up of additional Xenon reactivity load following a reactor trip can cause an extended (approximately 40 hours) of reactor shutdown**
- **this module presents the physical considerations that are needed to understand the importance of fission product positions in nuclear reactor control**



2. REACTIVITY EFFECTS OF FISSION PRODUCT POISONS

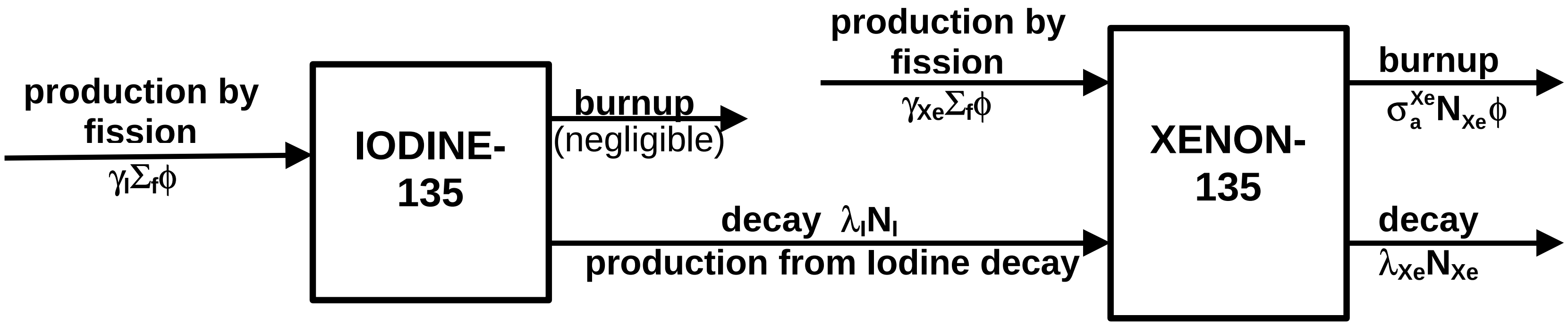
- **all fission products can be regarded as ‘reactor poisons’ because they all absorb neutrons to some extent and therefore reduce the multiplication factor**
- **most fission products build up slowly as the fuel ‘burns up’, and their effect is simply part of the decreasing fuel reactivity as a function of time and exposure to the neutron flux**
- **two fission products, Xenon-135 and Samarium-149 have particular importance in terms of reactor operation and control: these two nuclei have very large neutron absorption cross-sections and are produced in large quantities, directly from fission as well as from the decay of fission products**
- **Xe-135 has a microscopic absorption cross-section of 3.5×10^6 barns at thermal energies, and a total fission product yield of 6.6%; it is also radioactive, and its production from both direct fission and fission product decay in combination with its burn-up and own decay result in a complex impact on reactor operations**
- **Sm-149 has an absorption cross-section of 4.2×10^4 barns, a total fission product yield of 1.4%, and is a stable isotope**
- **the effect of both of these fission product poisons is to reduce the thermal utilization factor (f), so these fission product poisons are regarded as sources of negative reactivity (note that by comparison the microscopic absorption cross-section of natural uranium is 7.58 barns)**

3. XENON REACTIVITY BUILDUP

- **Xenon-135 (often simply referred to as ‘Xenon’) is produced in the fuel in two ways:**
  - ⇒ **directly from fission, Xe-135 forms about 0.3% of all fission products ($\gamma_{Xe} = 0.003$)**
  - ⇒ **indirectly from the decay of Iodine-135, which is formed both as a fission product and from the decay of the fission product Tellurium-135**

$$ {}^{135}_{52}\mathrm{Te} \xrightarrow[t_{½} = 19\ \mathrm{s}]{\beta,\ \gamma} {}^{135}_{53}\mathrm{I} \xrightarrow[t_{½} = 6.7\ \mathrm{h}]{\beta,\ \gamma} {}^{135}_{54}\mathrm{Xe} $$

- **together Te-135 and I-135 constitute about 6.3% of all fission products, and since the half-life of Te-135 is much shorter than that of I-135, for our purposes we can assume that all the I-135 is produced directly from fission ($\gamma_I = 0.063$)**
- **since the microscopic absorption cross-section of I-135 is small, its burn-up is negligible**
- **the following diagram illustrates the production and destruction of Xe-135**



3.1 Production and Loss Rates for Iodine and Xenon

- **considering a unit volume of the core, the production and loss rates of I-135 and Xe-135 can be formulated by subtracting the loss rates from the production rates**
- **for Iodine**

$$\frac{dN_I}{dt} = \gamma_I \Sigma_f \phi - \lambda_I N_I \tag{3D-1}$$

where N_I **= concentration of I-135 atoms per cm^3**

γ_I **= fission product yield of I-135 (0.063)**

Σ_f **= macroscopic fission cross-section**

ϕ **= average neutron flux**

λ_I **= decay constant of I-135 (2.87x10^{-5} sec^{-1})**

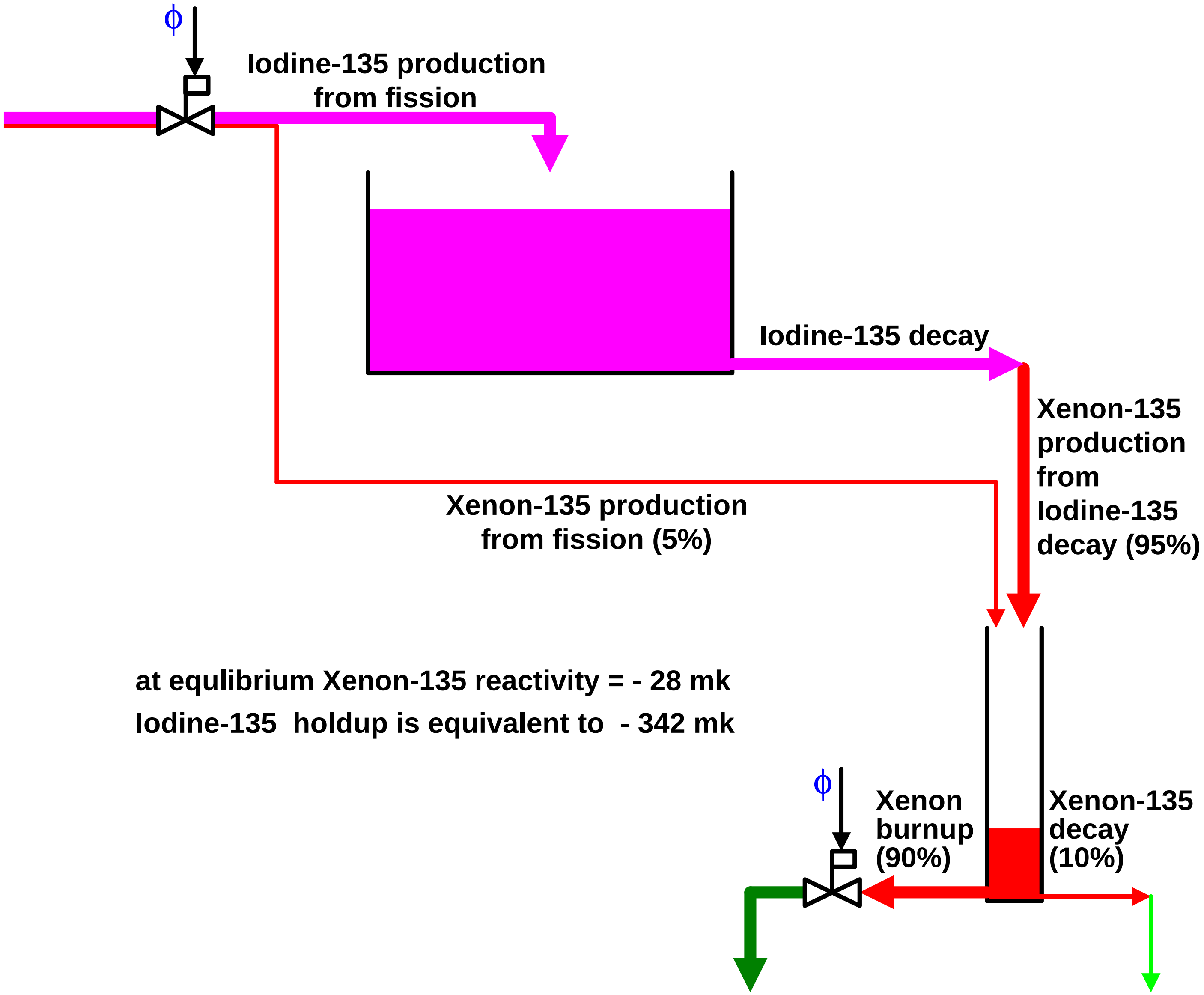
and the burnup rate of I-135 is assumed to be negligible

- **for Xe-135 the equation is more complicated, since there are two production terms (from fission and from the decay of Iodine) and two methods of loss (burnup and decay)**
- **using the same notation as above, we have:**

$$\frac{dN_{Xe}}{dt} = \underbrace{[\gamma_{Xe} \Sigma_f \phi + \lambda_I N_I]}_{\text{production term}} - \underbrace{[\lambda_{Xe} N_{Xe} + \sigma_a^{Xe} N_{Xe} \phi]}_{\text{loss term}} \tag{3D-2}$$

3.2 Water Tank Analogy for Xenon Production and Removal

- flows into and out of two tanks represent the production and removal of Iodine and Xenon, and the tank levels indicate the amounts of I-135 (mauve) and Xe-135 (red) in the fuel
- the tank levels remain constant as long as the inflow to each tank exactly matches the outflow
- the flows corresponding to radioactive decay are not dependent of flux
- the flows corresponding to production from fission and burnup depend on the neutron flux: if the reactor is shut down these flows stop (indicated by the closing of the valves)



at equlibrium Xenon-135 reactivity = - 28 mk

Iodine-135 holdup is equivalent to - 342 mk

4. IODINE AND XENON BUILD-UP TO EQUILIBRIUM CONCENTRATIONS

- **during the initial start-up of the reactor, or following an extended shutdown, there will be no I-135 and no Xe-135 in the fuel**
- **once the reactor has been started up and operated at full power, I-135 will be produced at a constant rate, i.e. there is a potential for the steady increase in the level of I-135**
- **since the rate of decay of I-135 is constant, as the level of Iodine concentration increases, so does the amount that decays**
- **steady state is reached when the level of production matches the level of decay**
- **from equation *(3D – 1)***

$$0 = \gamma_I \Sigma_f \phi - \lambda_I N_I$$

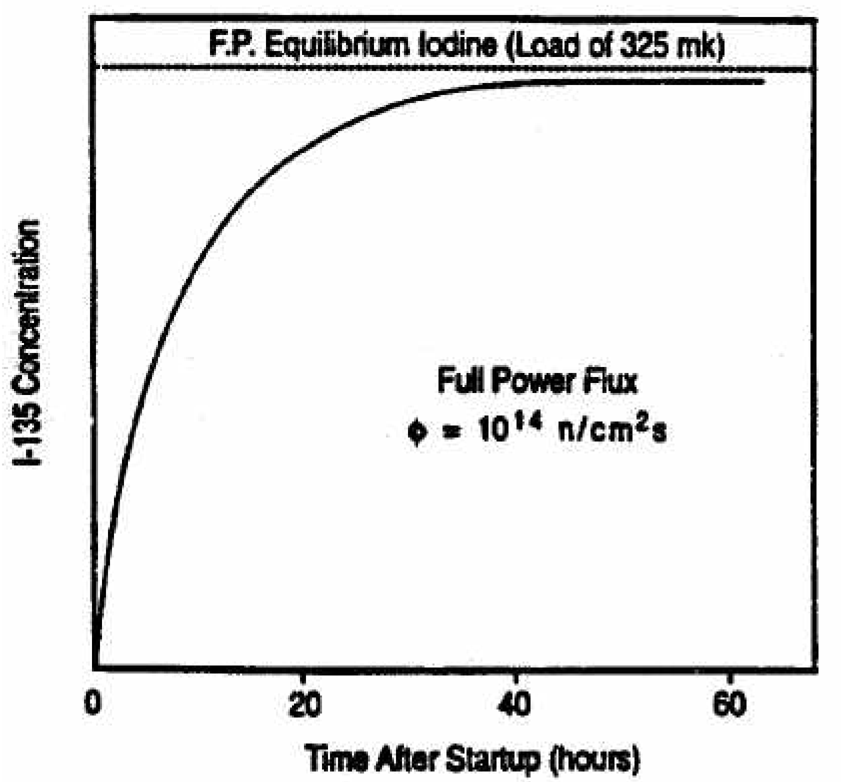
hence

$$N_{I(eq)} = \frac{\gamma_I \Sigma_f \phi}{\lambda_I}$$

- **as a function of time the build-up of I-135 is given by**

$$N_I = N_{I(eq)} \left(1 - e^{-\lambda_I t}\right)$$

- **the Iodine level will be within 2% of the equilibrium concentration after 40 hours of full power reactor operation**
- **note that the I-135 concentration is directly proportional to the thermal neutron flux**



4.1 Xenon-135 Buildup to Equilibrium

- **since Xenon-135 is produced mostly from Iodine-135 decay, Iodine needs to build up before there is significant Xenon production**
- **I-135 will have reached its equilibrium concentration sooner than Xe-135 because the half life of I-135 (6.7 hours) is shorter than that of Xe-135 (9.2 hours)**
- **at equilibrium, production and removal are equal, the rate of change of Xe-135 concentration is zero, and the I-135 has already reached its equilibrium value, giving**

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

- **at or near 100%FP the flux $\phi \cong 7\text{x}10^{13}$ n/cm^2 sec, $\lambda_{Xe} = 2.09\text{x}10^{-5}$ sec^{-1}, and**

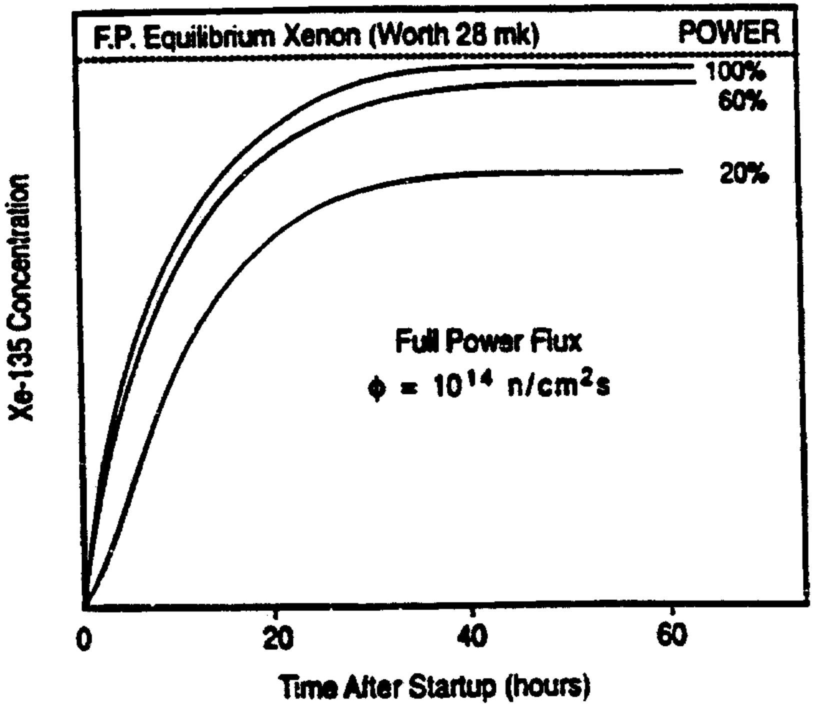
${}_a\sigma^{Xe}\phi = 3.5 \text{ x } 10^6 \text{ x } 10^{-24} \text{ x } 10^{13} = 24.5\text{x}10^{-5}$ sec^{-1} , i.e. the λ_{Xe} term can be ignored, giving

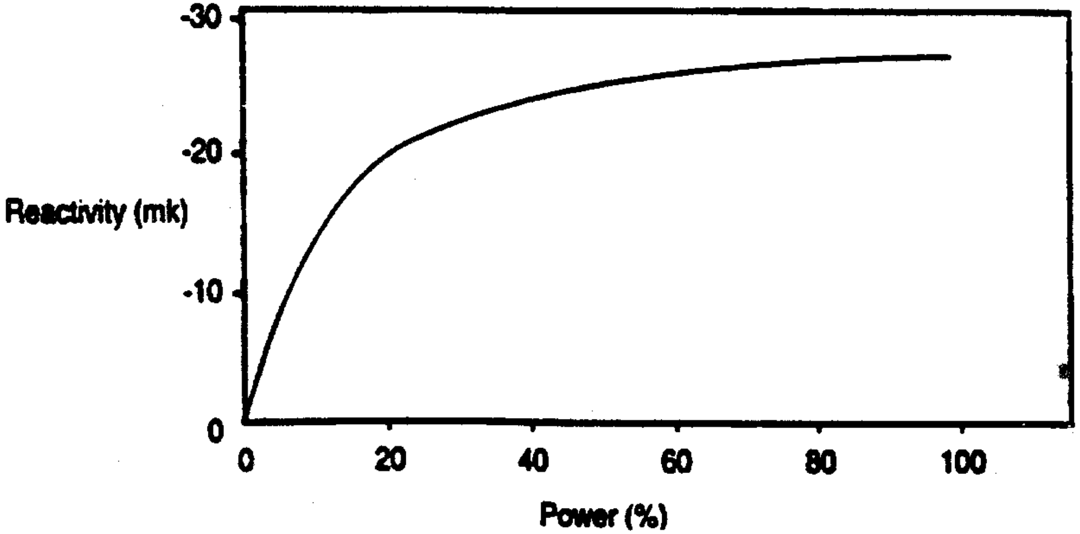
$$N_{Xe(eq)} = \frac{(\gamma_{Xe} + \gamma_I)\,\Sigma_f\ \phi}{\sigma_a^{Xe}\ \phi} = \frac{(\gamma_{Xe} + \gamma_I)\,\Sigma_f}{\sigma_a^{Xe}}$$

- **note that the Xe-135 concentration does not change by much as a function of reactor power level between 60% and 100&FP (different from Iodine, the concentration of which was directly proportional to power level)**
- **the Xenon level will be within 2% of the equilibrium concentration after 40 hours of full power reactor operation (same as for Iodine)**

4.2 Steady State Effects of Xenon Reactivity

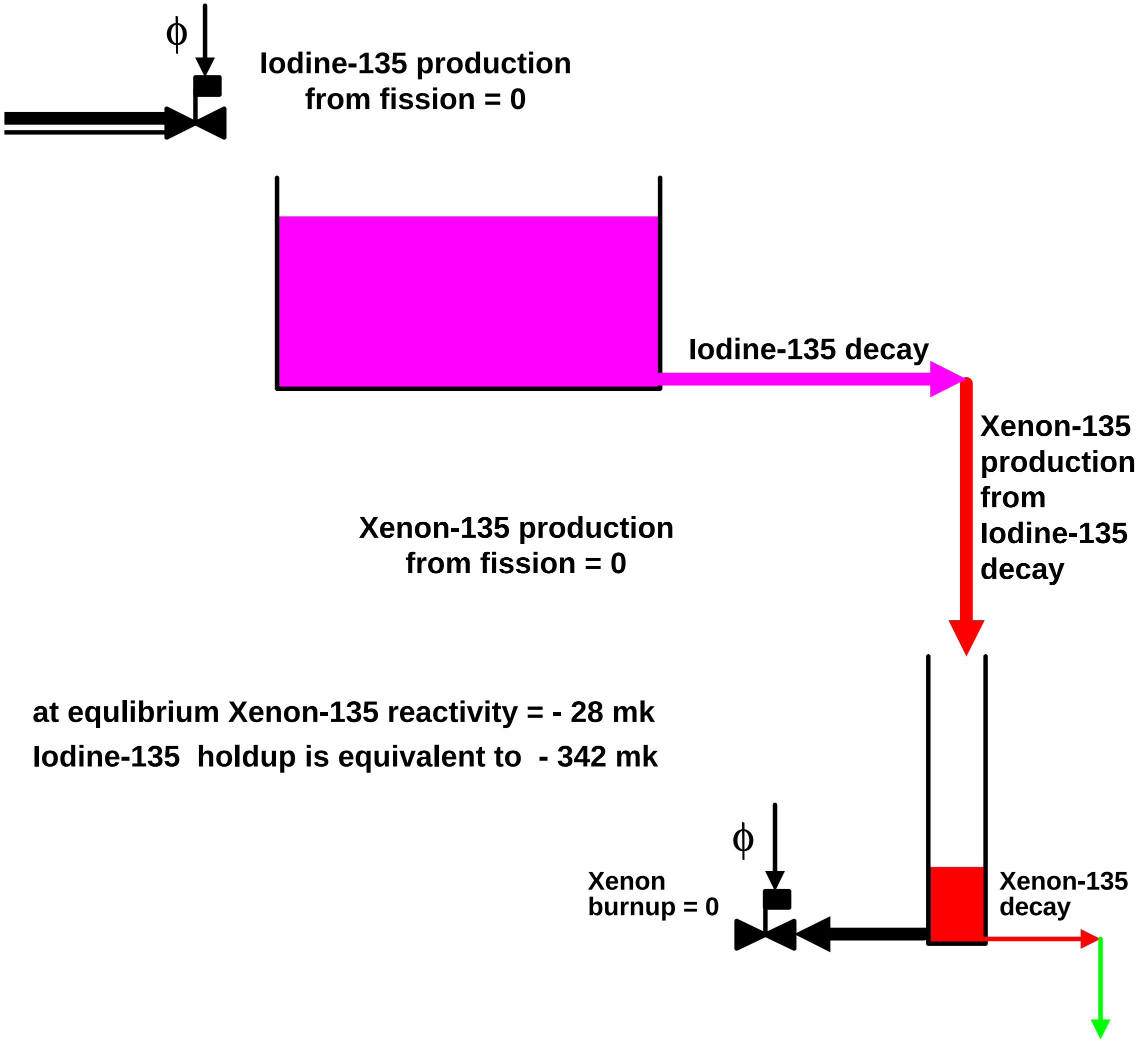
- **the Xenon reactivity 'load' in a CANDU 6 or 9 reactor operating at or near 100%FP is about –28 mk**
- **two aspects of reactor design need to be considered to deal with the Xenon steady state reactivity effect:**
  - ⇒ **the core design must contain sufficient positive reactivity to overcome the –28 mk due to Xenon**
  - ⇒ **since there is no Xenon in the reactor when it is first made critical, or after a long shutdown, the 28 mk of excess reactivity has to be compensated by other means, typically by desolving Boron in the moderator**
- **the concentration of Iodine-135 in the fuel does not by itself cause a reactivity effect, but it is recognized as a potential reactivity disturbance, called the 'iodine load' (approximately –325 mk), and is defined as the reactivity effect that would result if all the Iodine-135 in the fuel were to be converted to Xenon-135**





5. XENON TRANSIENT EFFECTS

- **the reactivity potential represented by the ‘Iodine load’, also referred to as the reactivity ‘hold-up’, becomes a real reactivity load whenever the reactor is shut down after it had operated for at least 40 hours at full power, i.e. when the Iodine load has built up to its equilibrium value**
- **when the neutron flux becomes essentially zero, the production of I-135, the production of Xe-135 from fission, and the burnup of Xe-135 all stop**
- **the production of X-135 from I-135 decay continues (95% of the steady state value), as does the decay of Xe-135 (10% of the steady state value), resulting in a rapid buildup of Xe-135**
- **the decay of Iodine-135 to Xenon-135 results in adding up to –320 mk of reactivity to the core, resulting in most power reactors ‘poisoning out’ for a period of two days, until the Iodine and the resultant Xenon decay and the corresponding reactivity load disappears**
- **particular care must be taken to add boron or other poison as the Xe-135 decays below its equilibrium value to ensure that the reactor does not go critical inadvertently**



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Iodine-135 holdup is equivalent to - 342 mk

5.1 Reactor Trip

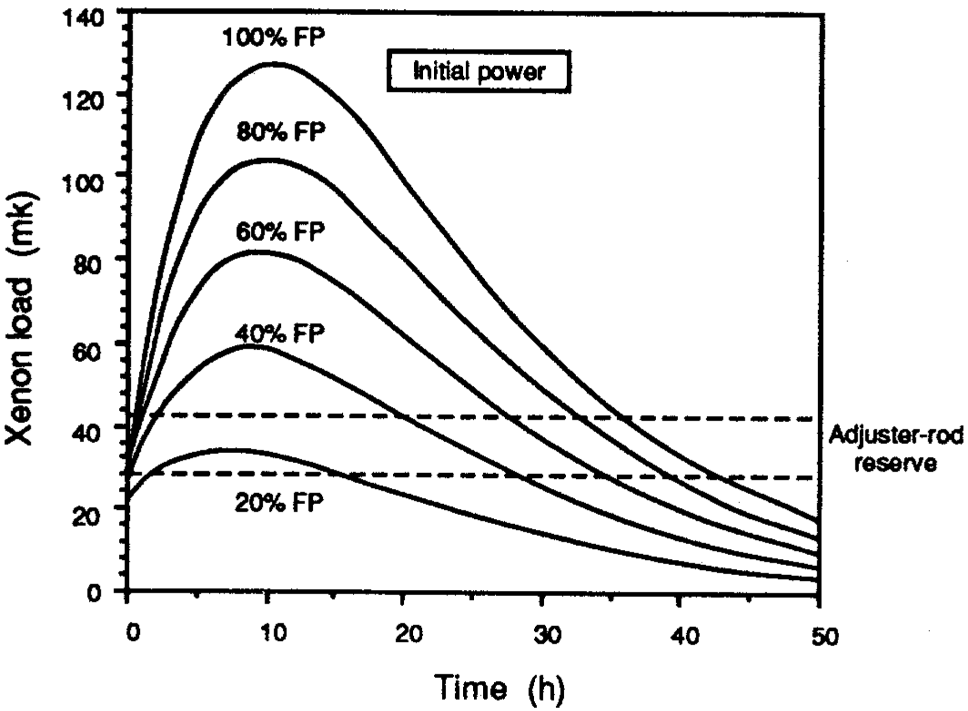
- **following a fast reactor shutdown such as a reactor trip, the Xenon reactivity rapidly builds up to a peak, i.e. to when Production of Xenon from Iodine decay = Loss of Xenon by Xenon decay**
- **the time period between the start of the Xenon transient and when the reactivity peak is reached is given by**

$$t_{peak} = \frac{1}{\lambda_I - \lambda_{Xe}} \ln\left[\frac{\lambda_I}{\lambda_{Xe}}\right] - \frac{1}{\lambda_I - \lambda_{Xe}} \ln\left[1 + \frac{(\lambda_I - \lambda_{Xe})}{\lambda_I} \cdot \frac{N_{Xe(eq)}}{N_{I(eq)}}\right]$$

- **the magnitude of the Xenon reactivity peak may be computed from**

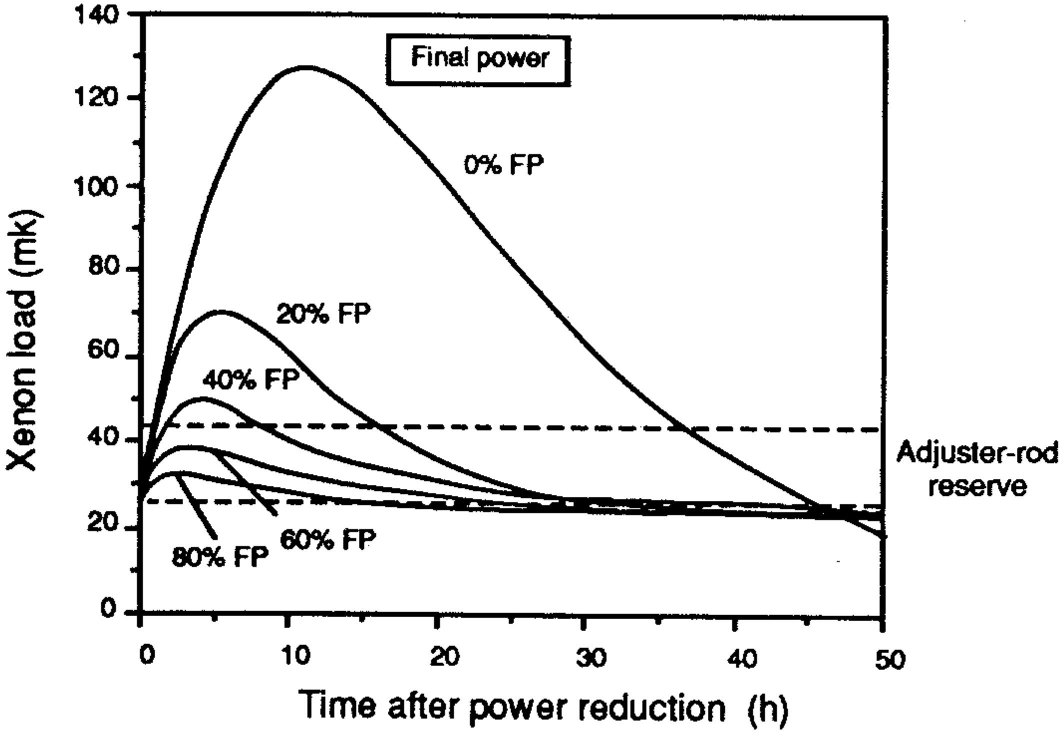
$$N_{Xe}^{peak} = \frac{\lambda_I}{\lambda_{Xe}} \cdot \frac{\gamma_I \Sigma_f \phi}{\lambda_I} \cdot e^{-\lambda_I t_{peak}}$$

- **the rate of rise of the Xenon load after a reactor trip from full power is typically in the order of 0.4 mk per minute for a CANDU, and the excess reactivity that can be provided by the adjuster rods is about 18 mk, so if the reactor cannot be returned to high power operations before the Xenon reactivity load has increased by this amount (45 minutes in this case) the reactor will 'poison out' i.e. it will take approximately 40 hours before the Xenon load decreases sufficiently to restart the reactor**
- **the diagram shows the Xenon Transients following reactor trips from various power levels**



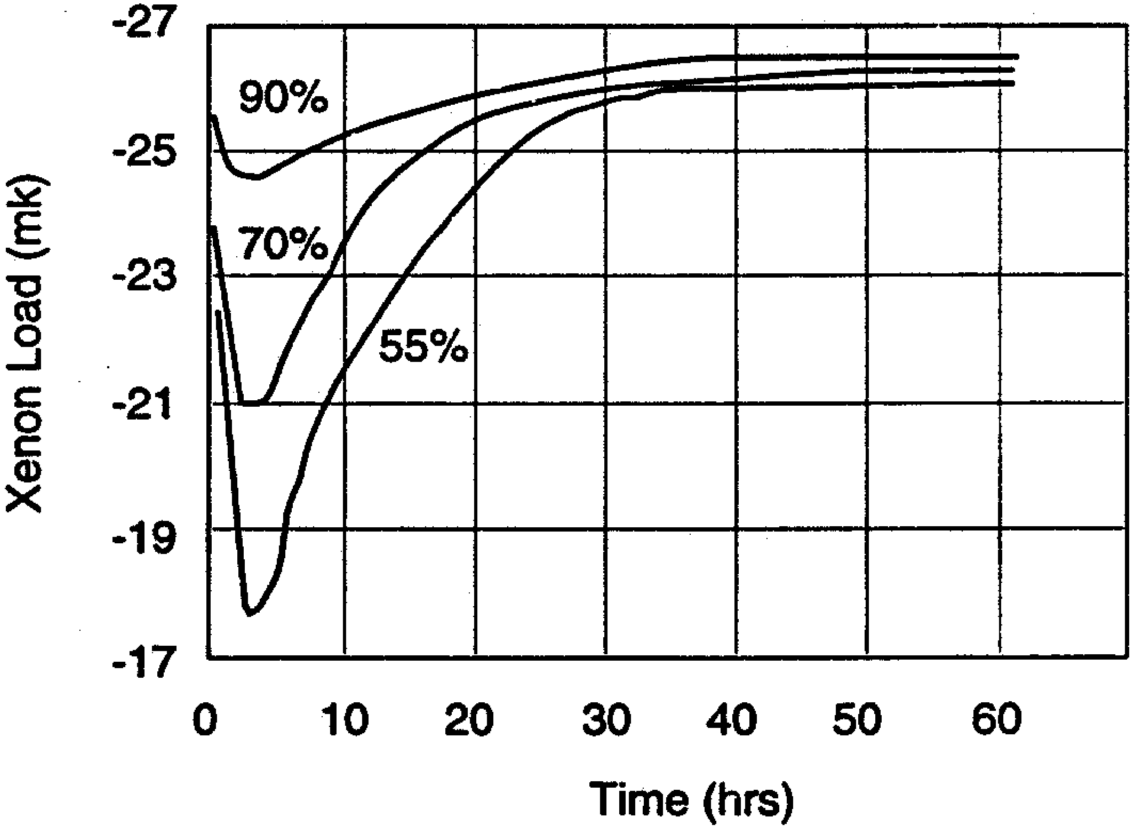
5.2 Poison Override

- **following a sudden reduction of reactor power, the time period within which the Xenon load can be overcome is called the 'poison override' time**
- **poison override will have occurred when the reactor power has been raised to a sufficiently high level that the rate of Xenon production $\leq$ Xenon loss; this is typically about 60%FP for CANDU reactors**
- **note that the time available between initiating the reactor trip and resetting it is appreciably less than the 45 minutes of 'poison override' time, because of the time needed to withdraw the shutdown rods, to take the reactor critical and to raise power to approximately 60%FP**
- **following the reactor trip the reactor operator must ensure that power is raised as rapidly as possible by inserting successive demanded power increases, but of course not o fast as to cause a rector trip on high log rate**
- **the Poison Override and Poison Out times will also be a function of the magnitude of the power reduction: the diagram shows the Xenon Transients as a function of the final power level after rapid power reductions from 100%FP**
- **note that although reactor power has to be raised to approximately 60%FP in order to prevent a poison out, it is not necessary that the unit be producing any electrical output: operating a unit under these conditions, with steam being bypassed to the condenser, is referred to as 'poison prevent' operation**



5.3 Xenon Transient Following a Power Increase

- **the previous sections were concerned with the effects of Xenon reactivity transients following power reductions: this is the main operational concern with Xenon, because of the potential for poison out**
- **following a power level increase from extended (≥ 40 hours) operations at a lower level, will cause a transient decrease in the Xenon load, since the Xenon burn-up rate has increased while the additional production of Xenon from Iodine will not appear for some time,**
- **the Xenon transient will start by decreasing the Xenon load, until it reaches a minimum, followed by an increase to the new equilibrium value**
- **this temporary net positive reactivity increase is not usually a problem in reactor operations, as the magnitude of the change should be within the normal range of control by the reactivity mechanisms**
- **advantage of this type of response can be taken if there is a need to extend the poison override time for a short planned reactor shutdown, by operating the reactor at a reduced power level, then raising reactor power so as to induce the desired amount of reduction in Xenon load, then tripping the reactor when the Xenon load is at its minimum**



6. ILLUSTRATION OF XENON TRANSIENT TERMINOLOGY

- **reactor start-up at time = 0 after a shutdown of one month**
- **reactor trip at t = 50 hours**