



U.S.NRC

United States Nuclear Regulatory Commission

Protecting People and the Environment



Reactor Physics Review

Section 2.1

HRTD
Human Resources
Training & Development





Learning Objectives



After studying this section, you should be able to:

1. Define the following terms:
 - a. $K_{\text{effective}}$
 - b. Reactivity
 - c. Reactivity Coefficient
 - d. Power Defect
 - e. Poison
 - f. Critical
 - g. Supercritical
 - h. Subcritical
 - i. Startup Rate





Learning Objectives



2. Describe the following reactivity coefficients and explain how their values change with core life and reactor power level:
 - a. Moderator Temperature
 - b. Doppler-Only Power
 - c. Void
 - d. Power





Learning Objectives



3. Explain the relative effects of the following poisons in plant operation:
 - a. Xenon
 - b. Samarium

4. Explain how the following controllable poisons affect core reactivity:
 - a. Control rods
 - b. Chemical shim





Learning Objectives



5. Explain the inherent response of the reactor to the following transients:
 - a. Secondary load changes
 - b. Reactivity additions from control rod motion or boron concentration changes
6. Explain how the neutron population of a subcritical reactor changes in response to reactivity changes.





Typical Fission Reaction



U-235 + neutron -----> U-236* ----->

FP₁ + FP₂ + 2.43 neutrons + energy

FP = Fission Product





Fuel



- U-235 (2% - 5%)
- U-238 (95% - 98%)
- Pu-239 (Created during reactor operations)





Typical Power Production at BOL & EOL



	BOL	EOL
U-235	93%	49%
U-238	7%	7%
Pu-239	0%	44%





Isotope	Neutrons
U-233	2.51
U-235	2.43
U-238 (fast fission)	2.47
Pu-239	2.90
Pu-241	3.06

Table 2.1-2
Average Number of Neutrons per Fission





- ~ 200 MeV per fission.



<u>Instantaneous Energy Release</u>	<u>MeV/fission</u>
K.E. of fission fragments	165
Prompt γ energy	5
Capture γ energy	5
K.E. of prompt neutrons	7
Total	182
 <u>Delayed Energy Release</u>	
β energy from fission products	7
γ energy from fission products	8
Neutrinos (not usable)	10
Total	25

Table 2.1-1





Prompt Neutrons



- Neutrons produced directly from fission.
- Appear within 10^{-14} seconds after fission.
- Account for $\sim 99.35\%$ of total number of neutrons associated with the fissioning of a U-235 nucleus.





Delayed Neutrons



- Neutrons produced from decay of fission products (fission fragments).
- Created $\sim 10 - 13$ seconds after fission.
- Account for $\sim 0.65\%$ of total number of neutrons produced from U-235 fission.



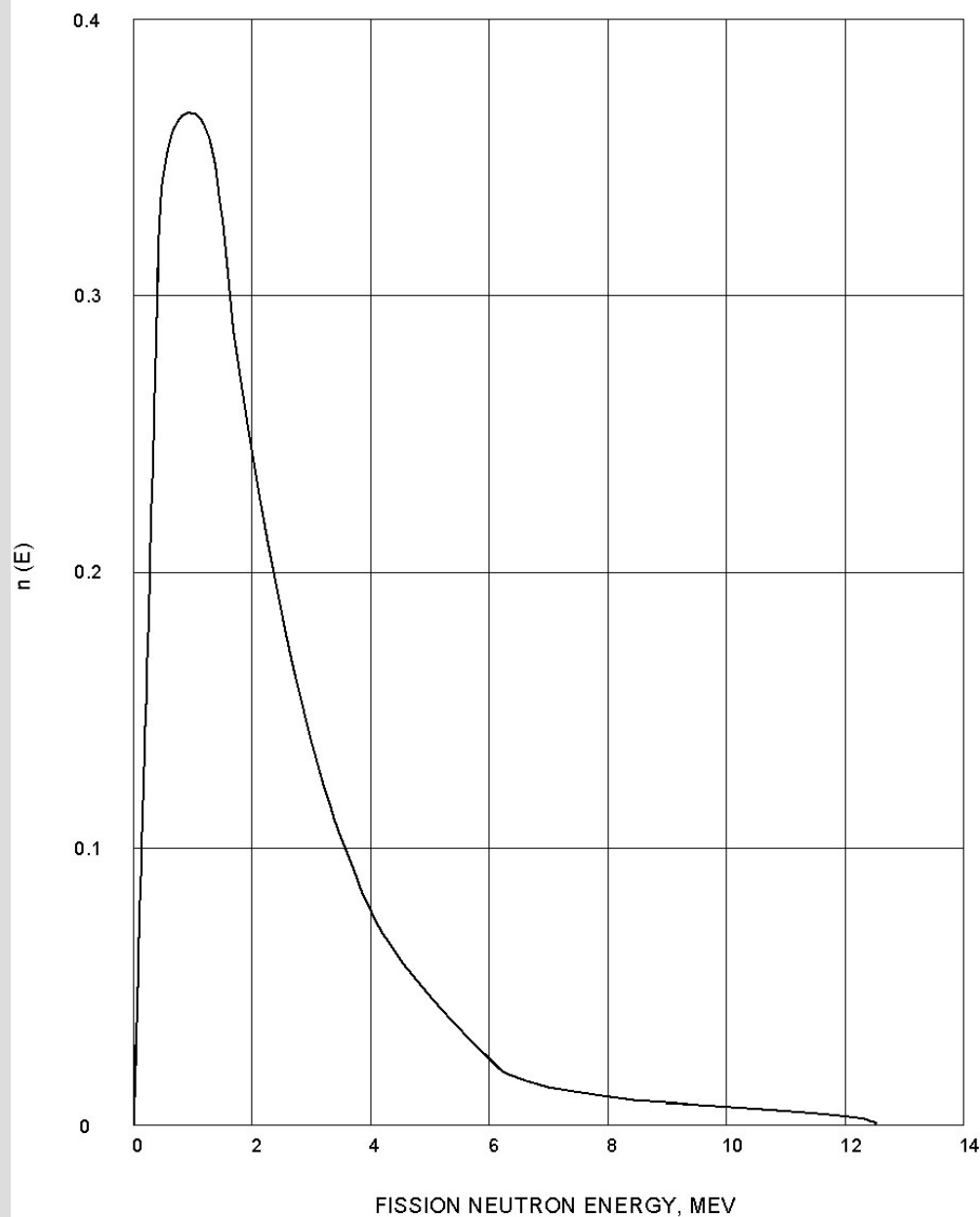


Neutron Cross Section



- A measure of the relative probability that a neutron will react with a particular nucleus is defined as the **neutron cross section** of the nucleus for that specified reaction.
- This measure is referred to as the **microscopic cross section (σ)**.
- $\sigma_T = \sigma_a + \sigma_s$
 $\sigma_a = \sigma_c + \sigma_f$





Fission Neutron Energies Fig 2.1-1

Figure 2.1-1 Fission Neutron Energy



U-235 Fission Cross Section

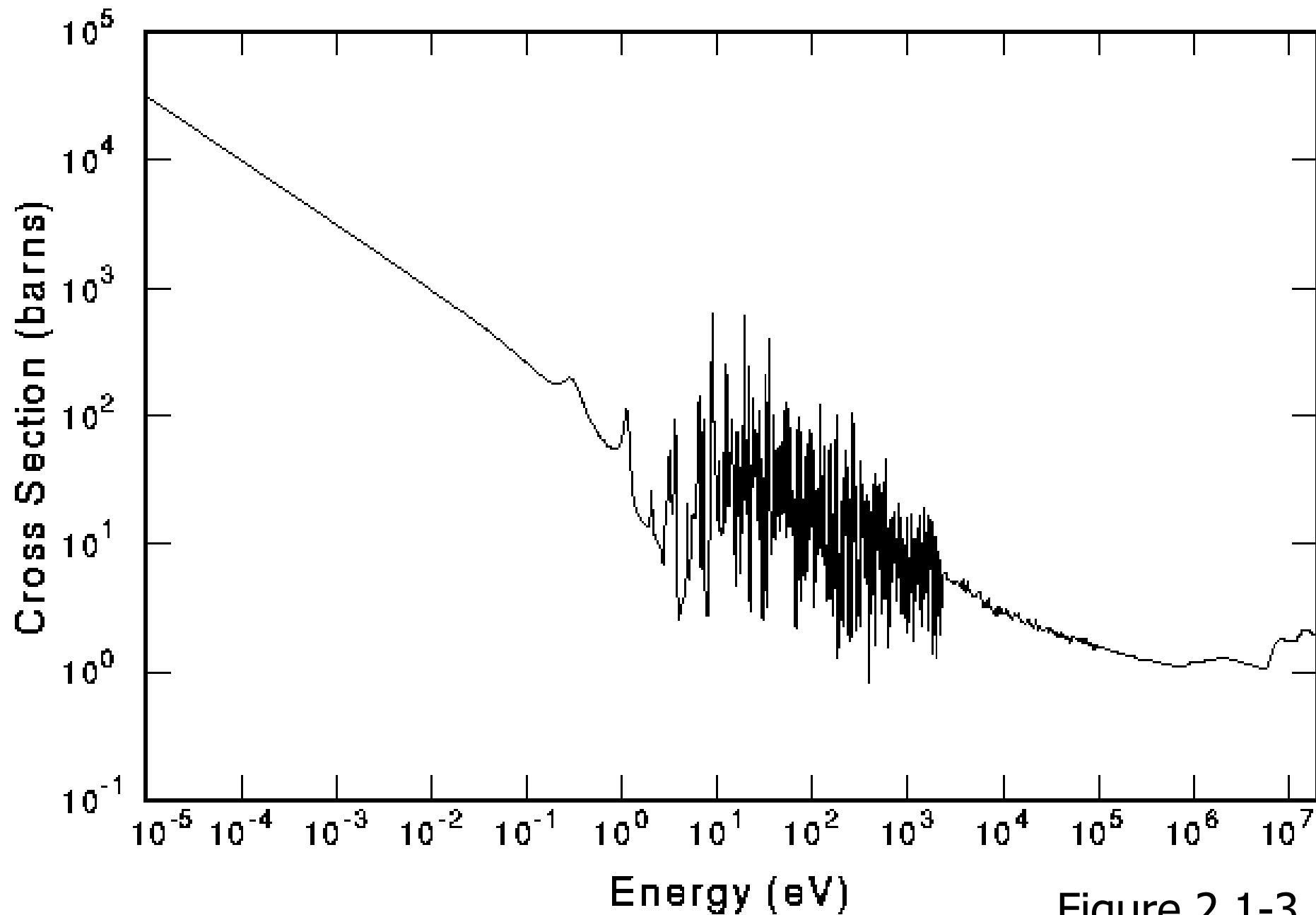


Figure 2.1-3



Neutron Moderation



- ☞ A neutron must be greatly slowed down (≤ 1 eV) to have a high probability of causing fission in U-235.
- ☞ A slowed neutron is also called a “thermal” neutron, since it is in thermal equilibrium with its environment.
- ☞ The process of slowing down neutrons is called “moderation.”





Moderator



- The medium used to slow neutrons down is called the “moderator.”
- Water is the moderator in a PWR. Neutrons are slowed down through collisions with the hydrogen atoms of the water molecules (elastic scattering).
- About 17 collisions are required to slow a neutron to thermal energy.





Neutron Reactions



- As a neutron slows down from fission energy to thermal energy via collisions with the moderator, one of two fates awaits it:
 - It is absorbed by a nucleus.
- OR
- It leaks out of the core.





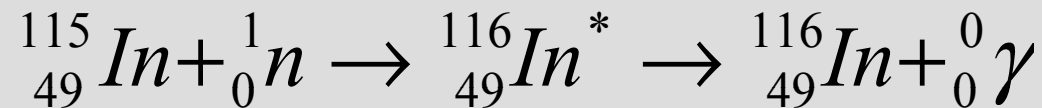
Absorption Reactions



- If a neutron is absorbed, it is either captured or causes fission.

- Neutron capture:

Radiative capture:



Charged particle emission:



- Fission





The possibilities are all mathematically described in the 6 factor formula.

- Each factor in the formula relates to a possible “fate” of a given neutron.
- The product of all 6 factors is the ratio of fission neutrons from one “generation” to the next.





Effective Multiplication Factor



- **$K_{\text{effective}}$** is a measure of the change in fission neutron population from one neutron generation to the next,

or

$$K_{\text{effective}} = \frac{\text{\# of fission neutrons in this generation}}{\text{\# of neutrons in the previous generation}}$$

$$K_{\text{eff}} = \frac{N}{N_0}$$





Six Factor Formula



$$K_{eff} = \epsilon L_f p L_{th} f \eta$$

Where:

ϵ (epsilon) = *fast fission factor*

L_f = *fast nonleakage factor*

p = *resonance escape probability*

L_{th} = *thermal nonleakage factor*

f = *thermal utilization factor*

η (eta) = *neutron production factor*





$K_{\text{effective}}$



- If $N=N_0$, the reaction is self-sustaining.
 $K_{\text{eff}}=1$, and the reactor is **critical**.
- If $N<N_0$, neutron population is decreasing.
 $K_{\text{eff}}<1$, and the reactor is **subcritical**.
- If $N>N_0$, neutron population is increasing.
 $K_{\text{eff}}>1$, and the reactor is **supercritical**.





Reactivity



- In reactor physics, it is more convenient to use a term called **reactivity** rather than K_{eff} to describe the state of the reactor core.
- Reactivity (ρ or $\Delta K/K$) is defined in terms of K_{eff} by the following equation:

$$\rho = \frac{K_{eff} - 1}{K_{eff}}$$





Units of Reactivity



- $\frac{\Delta K}{K}$, $\% \frac{\Delta K}{K}$, and pcm.
- $1 \frac{\Delta K}{K} = 100 \% \frac{\Delta K}{K} = 10^5 \text{ pcm}$
- $\% \frac{\Delta K}{K}$ Used in Technical Specifications
- Percent millirho (pcm), used by Westinghouse





Reactivity vs. K_{eff}



Condition	K_{eff}	Reactivity (ρ)
Critical	1	0
Subcritical	<1	Negative
Supercritical	>1	Positive



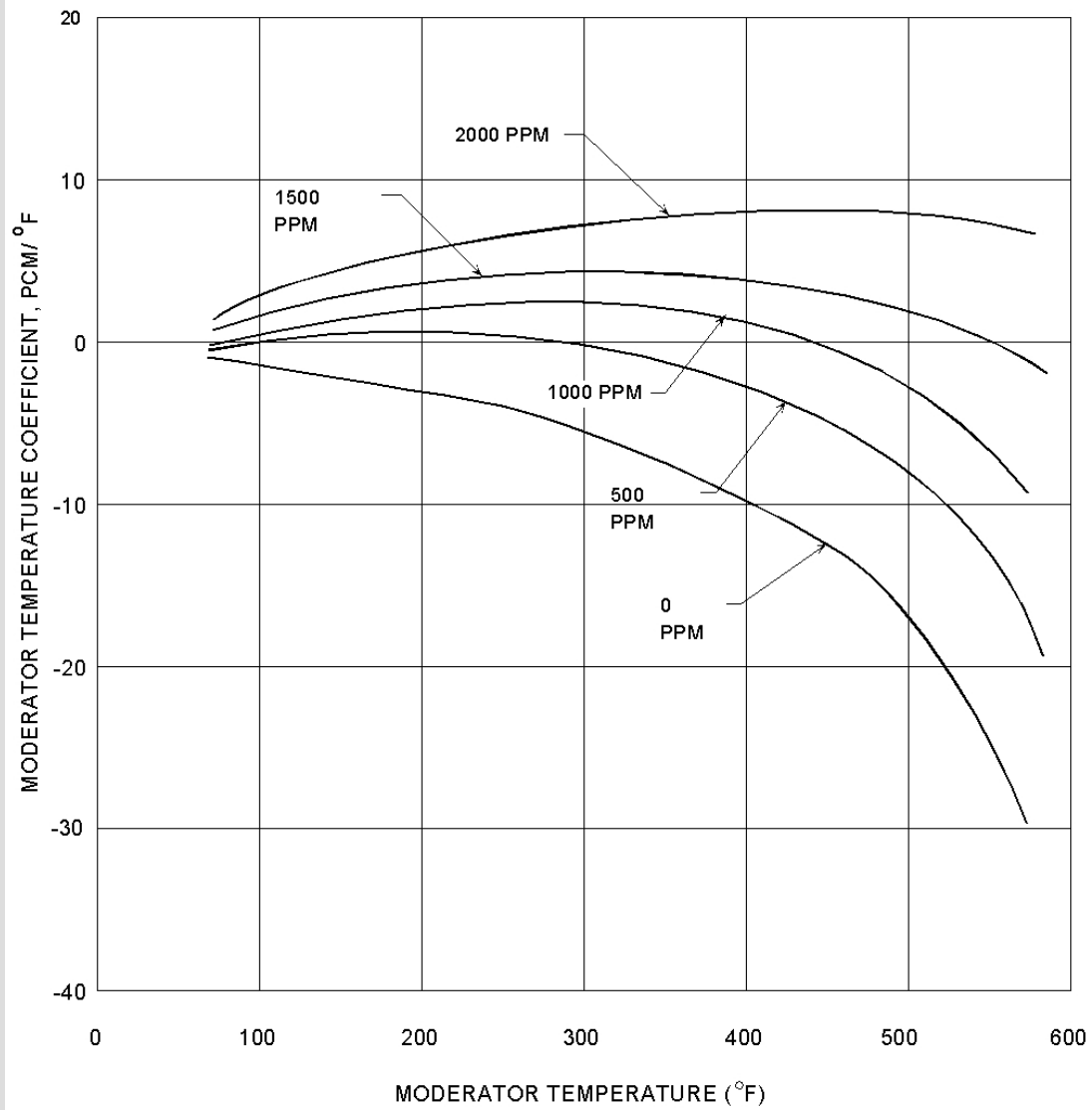


Reactivity Coefficients



- A reactivity coefficient is defined as the change in reactivity with respect to the unit change in some operating parameter of the reactor (e.g., temperature, pressure).





MTC Fig 2.1-8

Figure 2.1-8 Moderator Temperature Coefficient





Void Coefficient



- At high powers, a small amount of nucleate boiling occurs on the fuel pins.
- The steam bubbles (voids) represent a loss of moderation. Therefore, the void coefficient affects the same factors as the MTC.
- The void coefficient is defined as the change in reactivity as the result of boiling of the moderator in the core region and has the units of pcm / %void.





Void Coefficient



- The normal void content of the core is $\sim 0.5\%$.
- Changes from $-30 \text{ pcm}/\% \text{void}$ at BOL & low temperatures to $-250 \text{ pcm}/\% \text{void}$ at EOL & operating temperatures.
- This coefficient only has a significant effect in accidents.





Pressure Coefficient



- Water density increases slightly as pressure is increased.
- The pressure coefficient is a change in reactivity caused by a change in pressure on the primary system.
- The pressure coefficient is affected by the same mechanisms that change the moderator temperature and void coefficients.
- This coefficient is negligible in a PWR and will not be used to explain any phenomena (we will probably never mention it again).



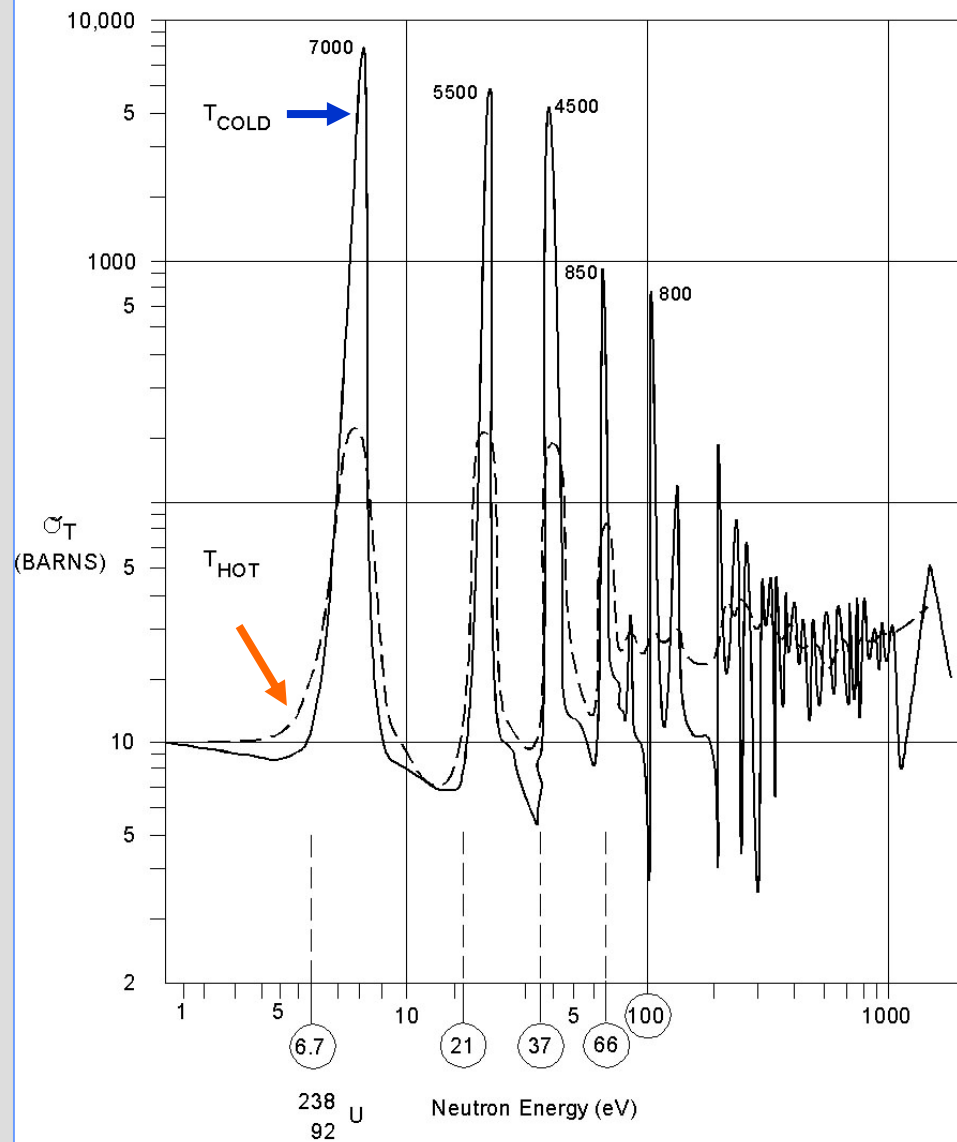


Fuel Temperature Coefficient



- The fuel temperature coefficient, also called Doppler coefficient of reactivity, is the reactivity change that results from a change in the resonance cross section of the fuel due to a change of fuel temperature.
- It is brought about by the nature of some fuel materials, principally U-238 and Pu-240.



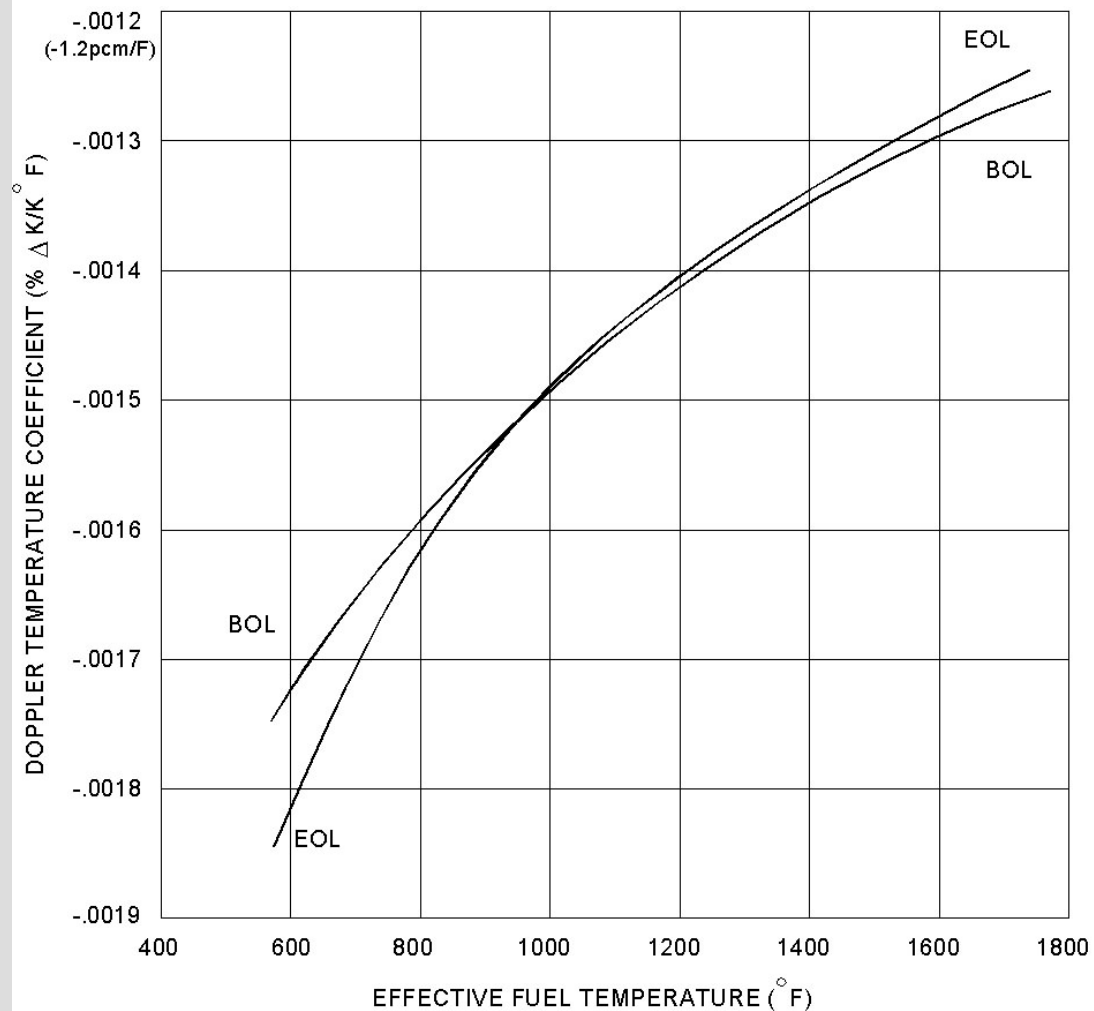


Cross Section Curve

Fig 2.1-4

Figure 2.1-4 Cross Section Curve

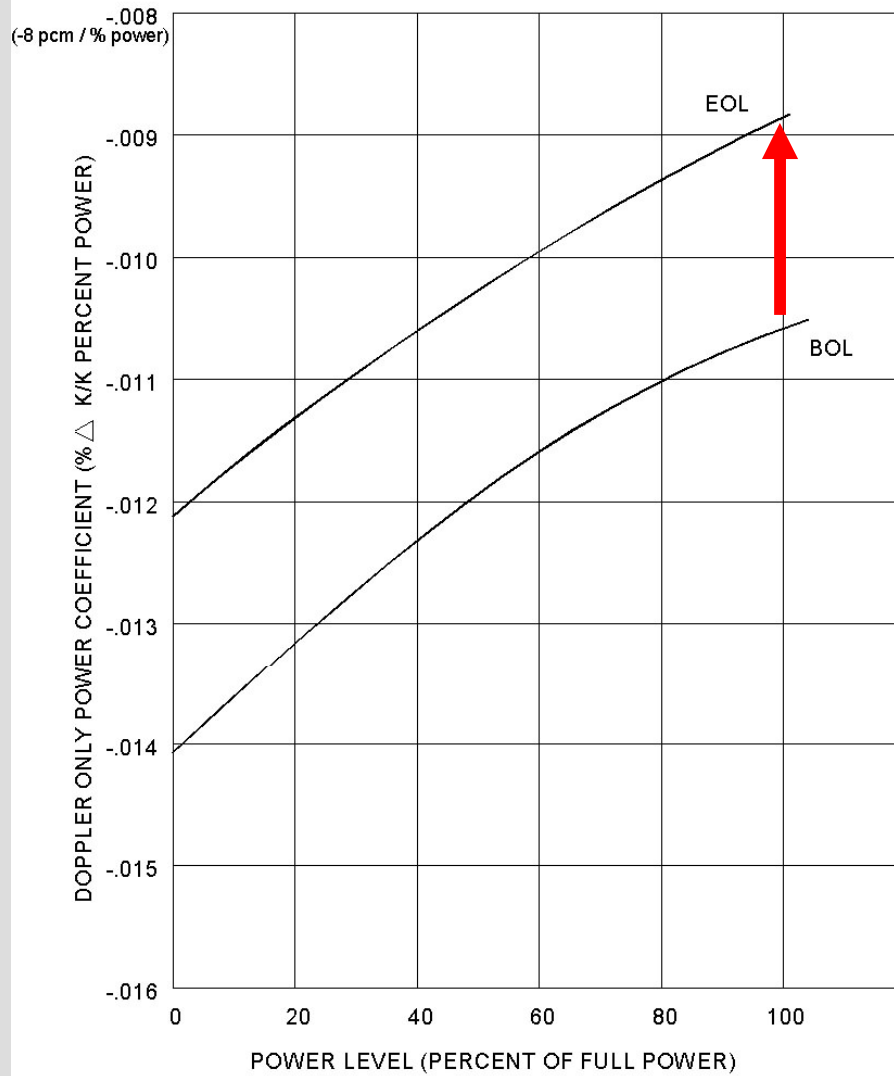




Fuel Temp Coefficient

Fig 2.1-5

Figure 2.1-5 Doppler Temperature Coefficient, BOL and EOL

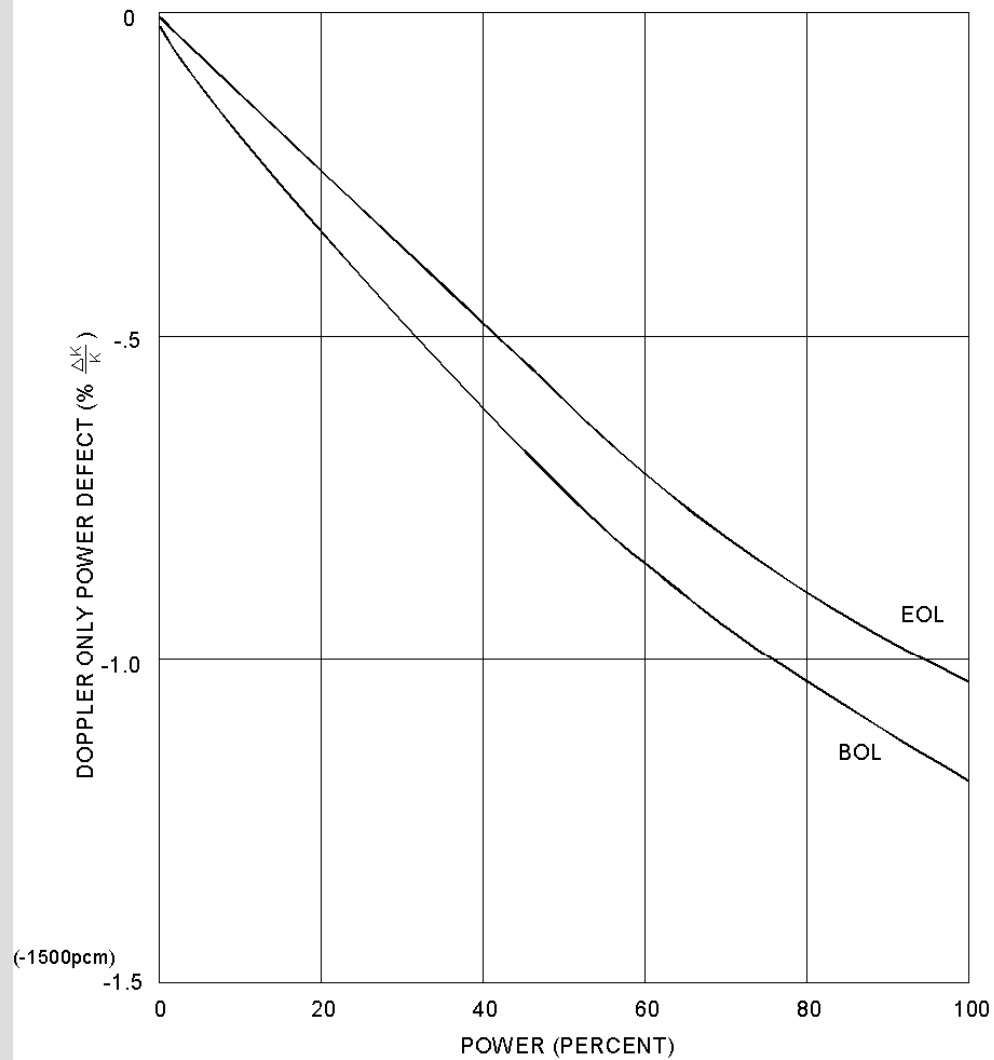


Doppler-Only Power Coefficient

Fig 2.1-6

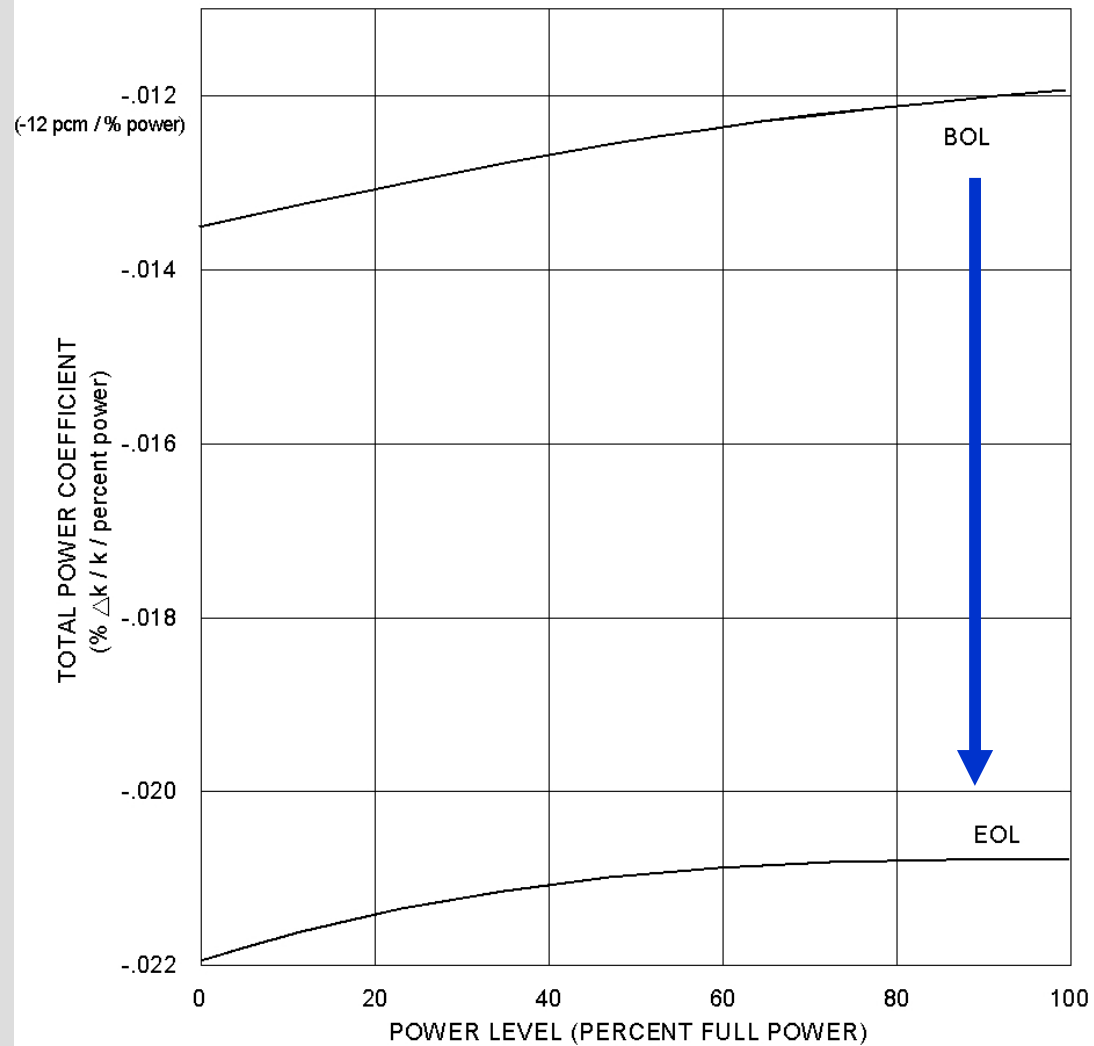
Figure 2.1-6 Doppler Only Power Coefficient, BOL and EOL





Doppler-Only Power Defect Fig 2.1-7

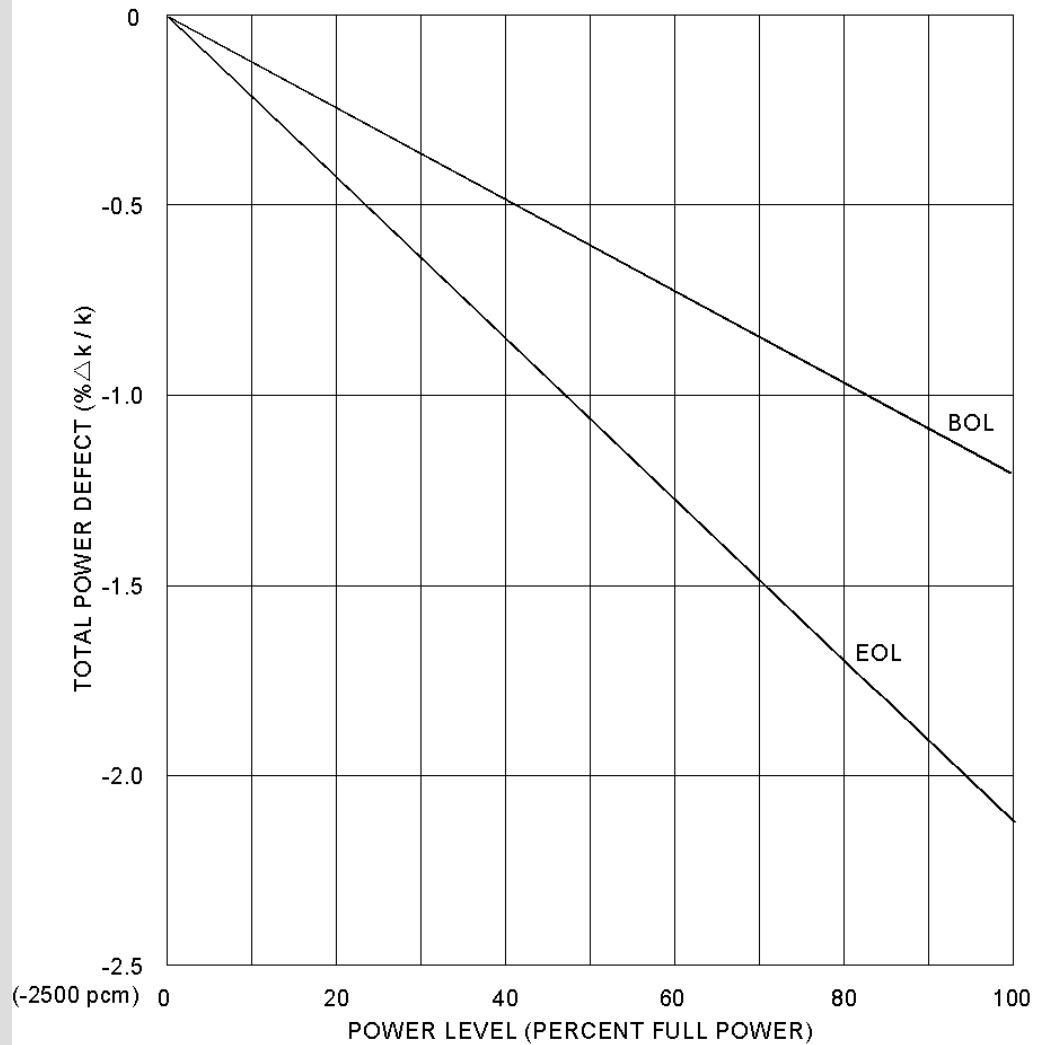
Figure 2.1-7 Doppler Only Power Defect, BOL and EOL



Power Coefficient Fig 2.1-9

Figure 2.1-9 Total Power Coefficient, BOL and EOL





Power Defect Fig 2.1-10

Figure 2.1-10 Total Power Defect, BOL and EOL





Neutron Poisons



- In a reactor system, poisons absorb neutrons without causing fission.
- Control rods and boron are examples of poisons which are controlled by the operator.
- Xenon and samarium are examples of poisons which are not controlled by the operator.





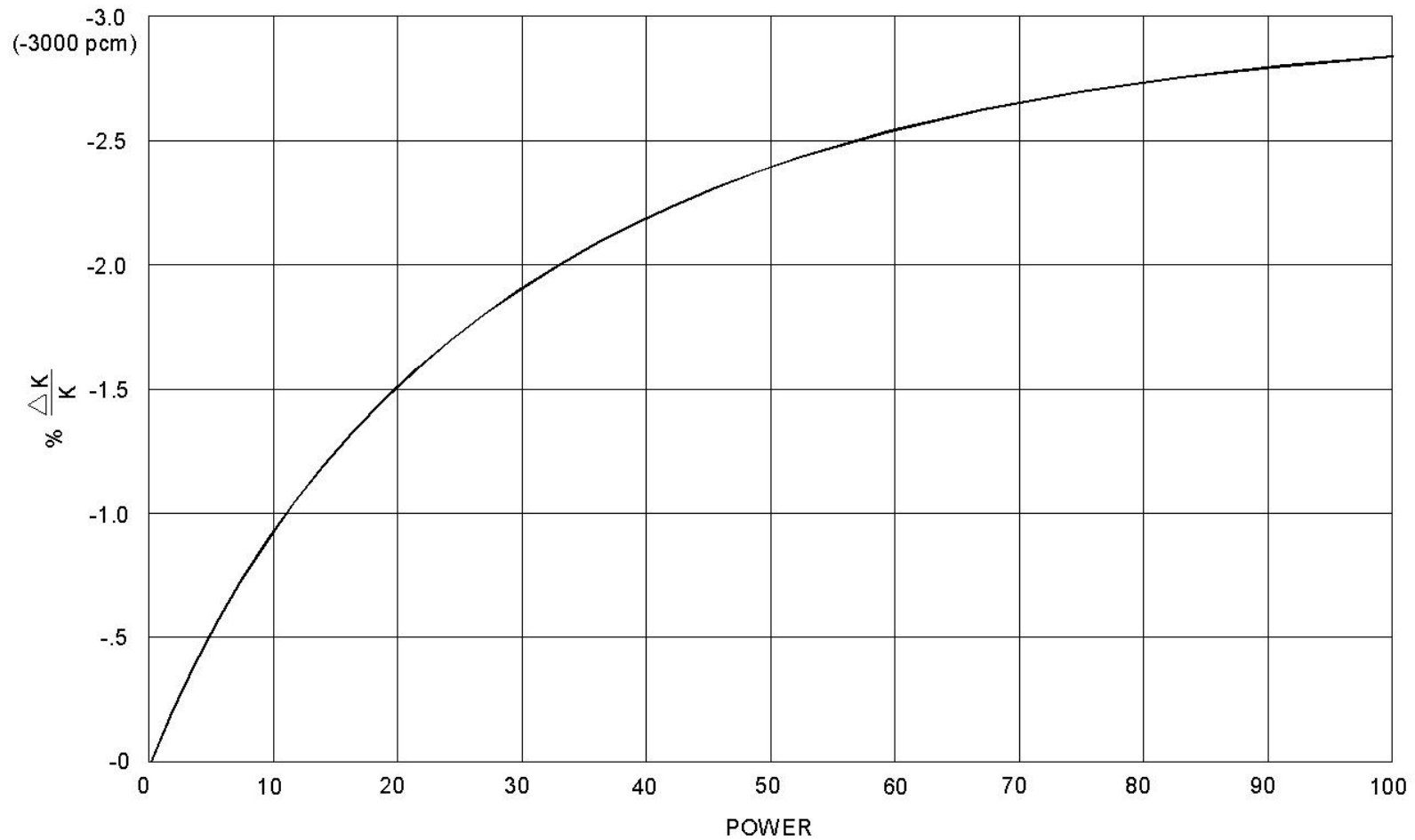
Xenon



- Xenon is a fission product poison with a microscopic absorption cross section of 2.6 million barns.
- Xenon reactivity at 100% equilibrium concentration is ~ -2800 pcm.



Figure 2.1-12 Equilibrium Xenon Worth vs Percent of Full Power



Equilibrium Xenon vs Power Fig 2.1-12





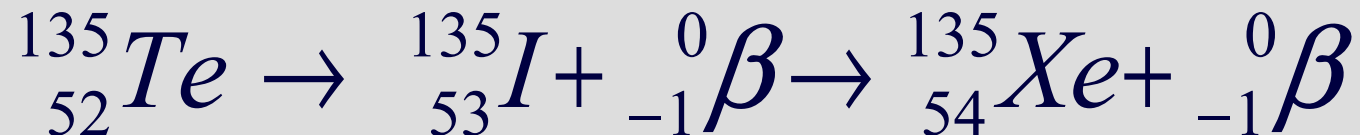
Xenon Buildup



- Xenon production:

Directly from fission (0.3% yield)

Decay of Tellurium (5.9% yield)



$$t_{\frac{1}{2}} = 19.2\text{ s} \qquad t_{\frac{1}{2}} = 6.7\text{ hr}$$

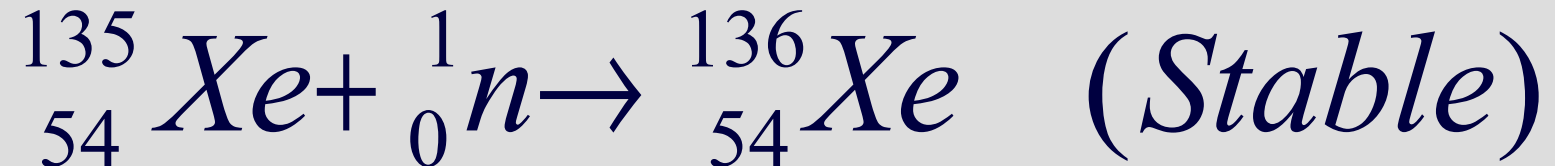




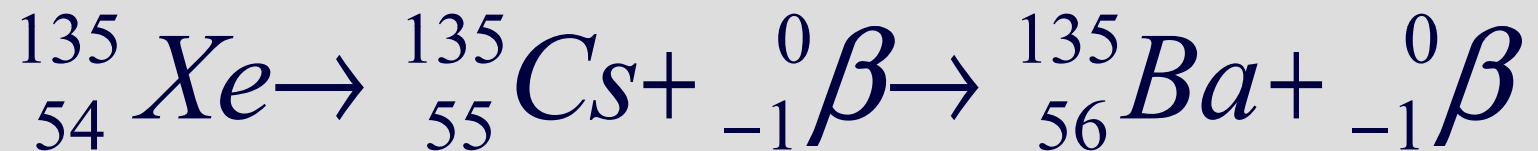
Xenon Removal



- Burnout



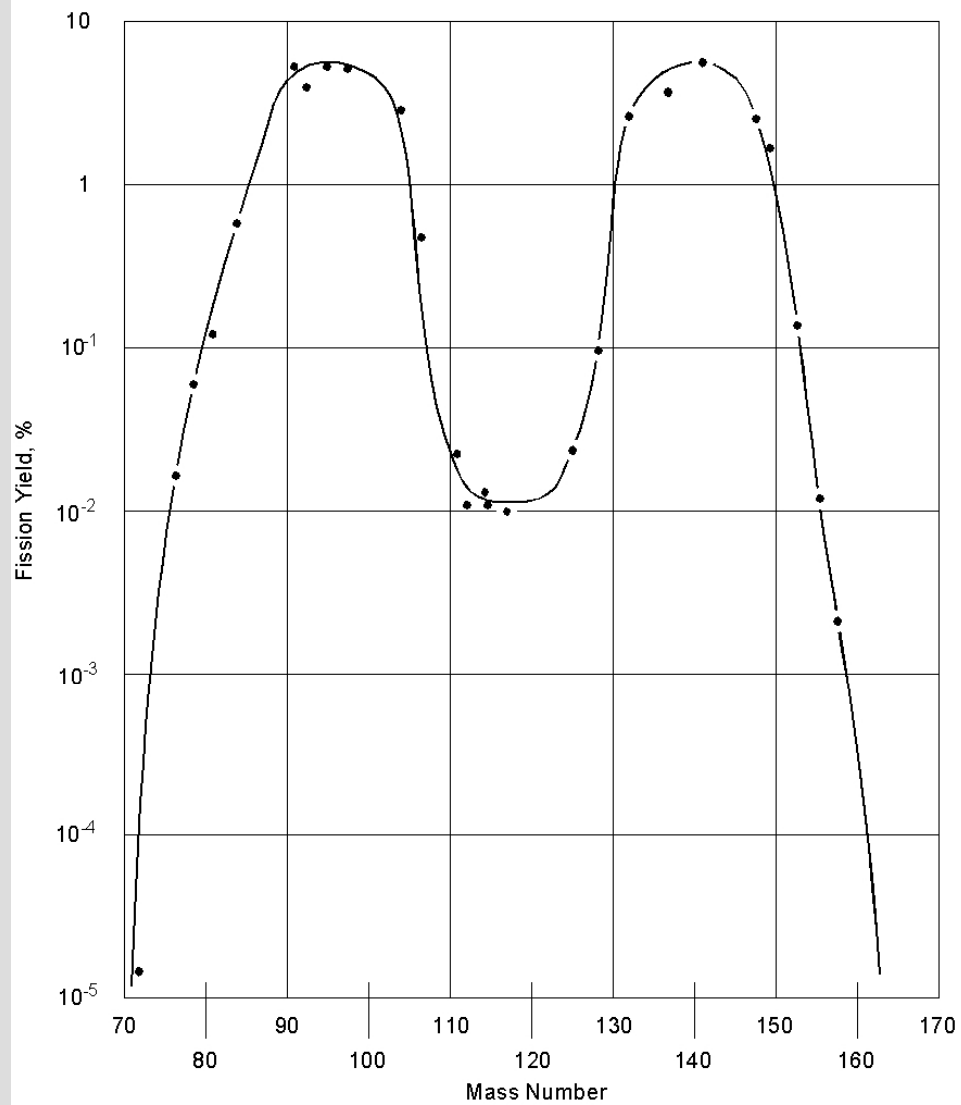
- Decay



$$t_{\frac{1}{2}} = 9.2h$$

$$t_{\frac{1}{2}} = 20000y$$





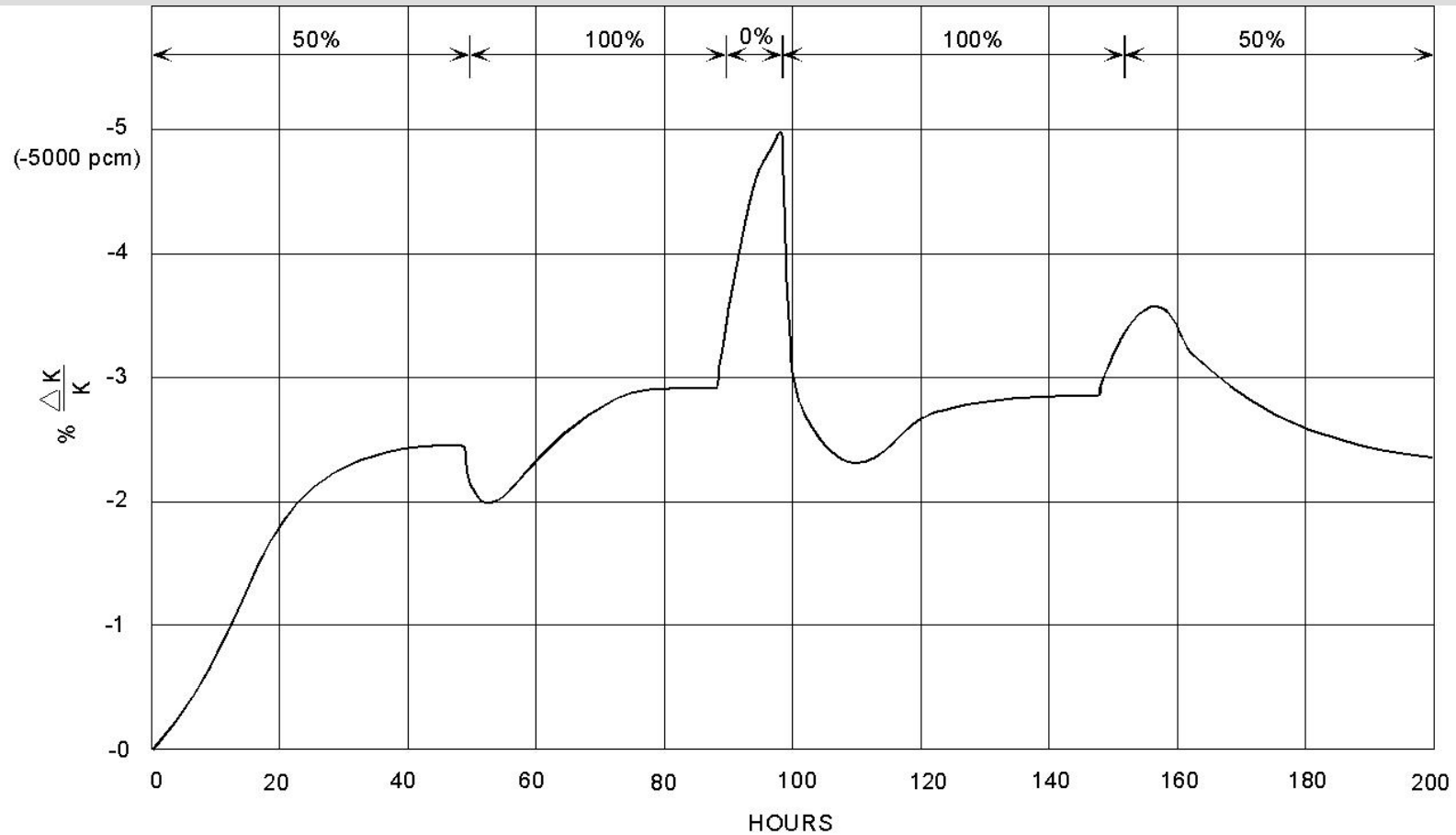
Fission Yield Fig 2.1-11

Figure 2.1-11 Fission Yield versus Mass Number





Figure 2.1-13 Xenon Transients

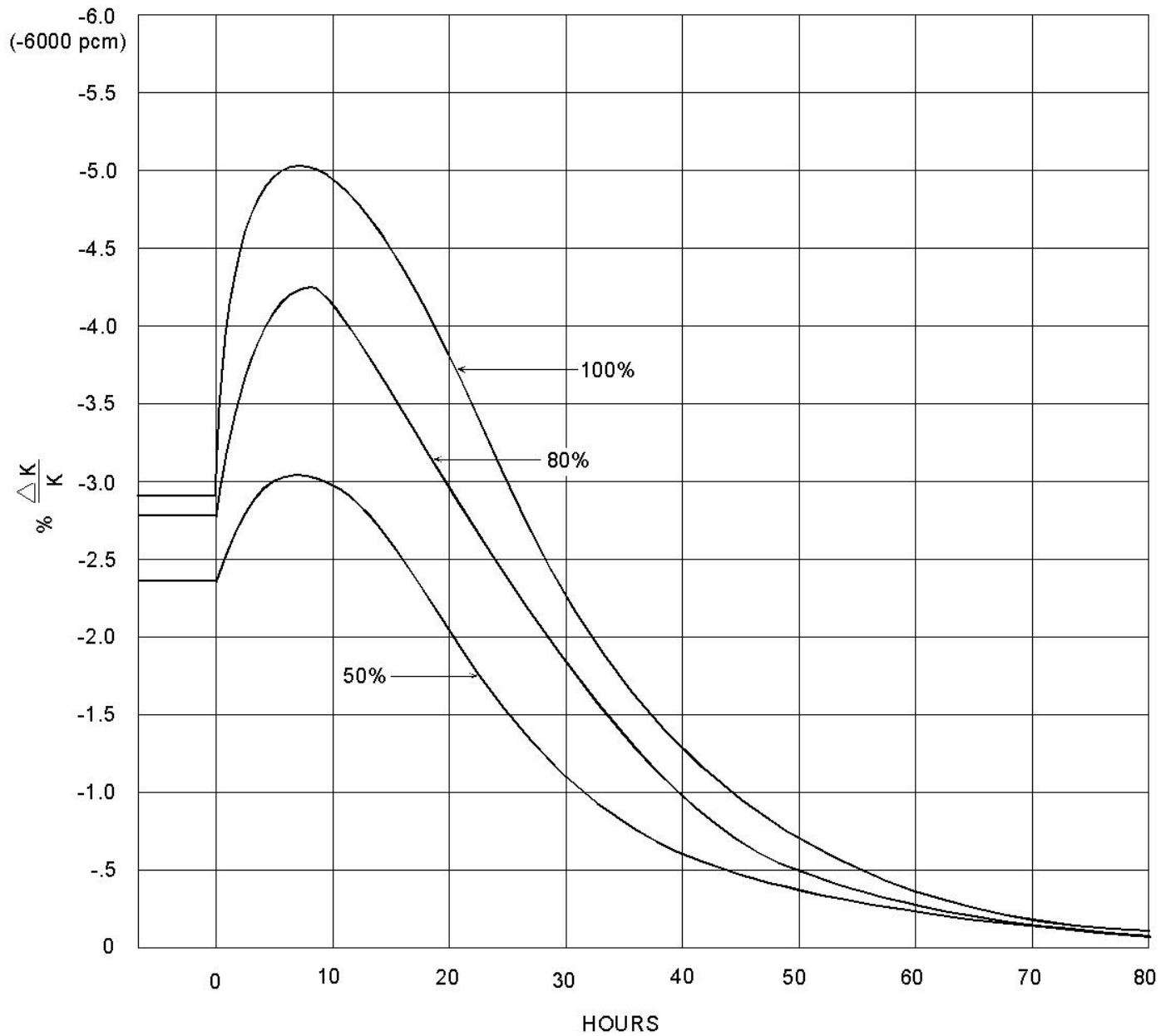


Xenon Transients Fig 2.1-13

Xe

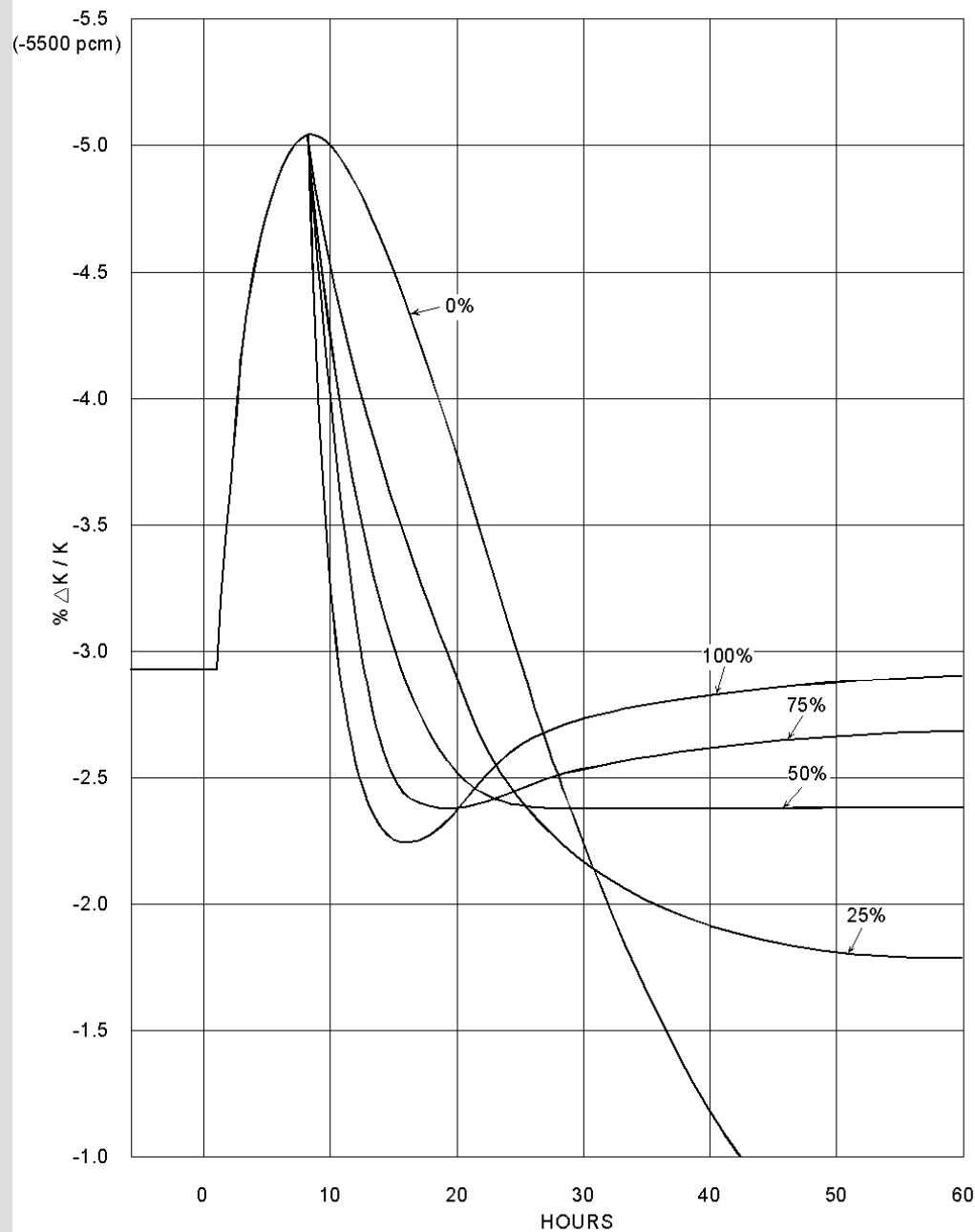


Figure 2.1-14 Xenon Transients Following a Reactor Trip



Post Trip Xenon Fig 2.1-14





Xenon Transients Fig 2.1-15

Figure 2.1-15 Xenon Transients Following a Reactor Trip and Return to Power



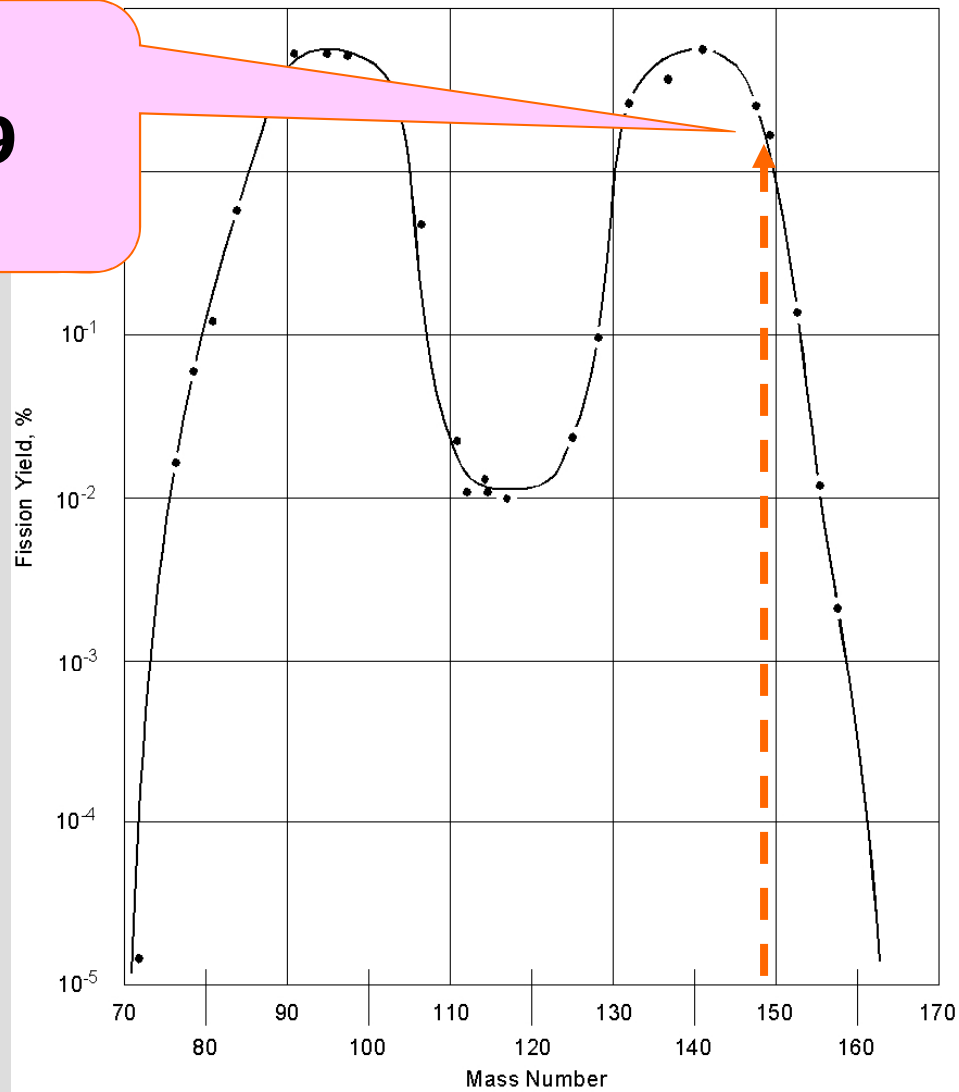
Samarium



- Samarium is a fission product poison (fission yield = 2.1%) with a microscopic cross section of 40,000 barns.
- Samarium reactivity at equilibrium concentrations is ~ -650 pcm.



Sm-149



Fission Yield Fig 2.1-11

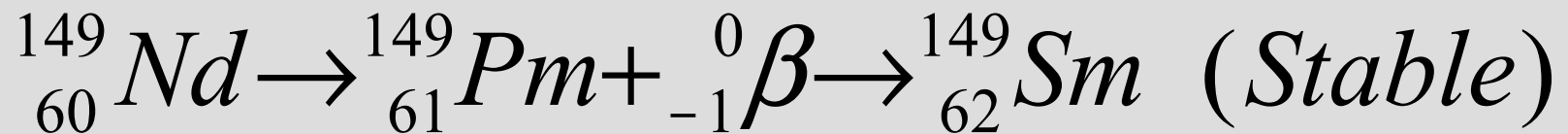
Figure 2.1-11 Fission Yield versus Mass Number



Samarium

Production/Removal

■ Production



$$t_{\frac{1}{2}} = 1.7h$$

$$t_{\frac{1}{2}} = 53h$$

■ Removal

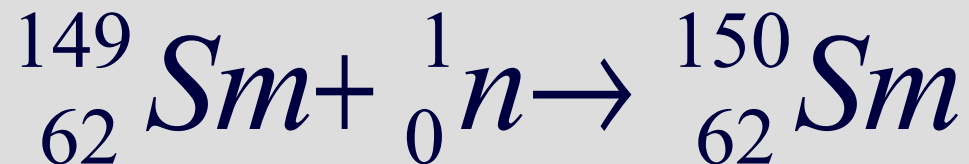
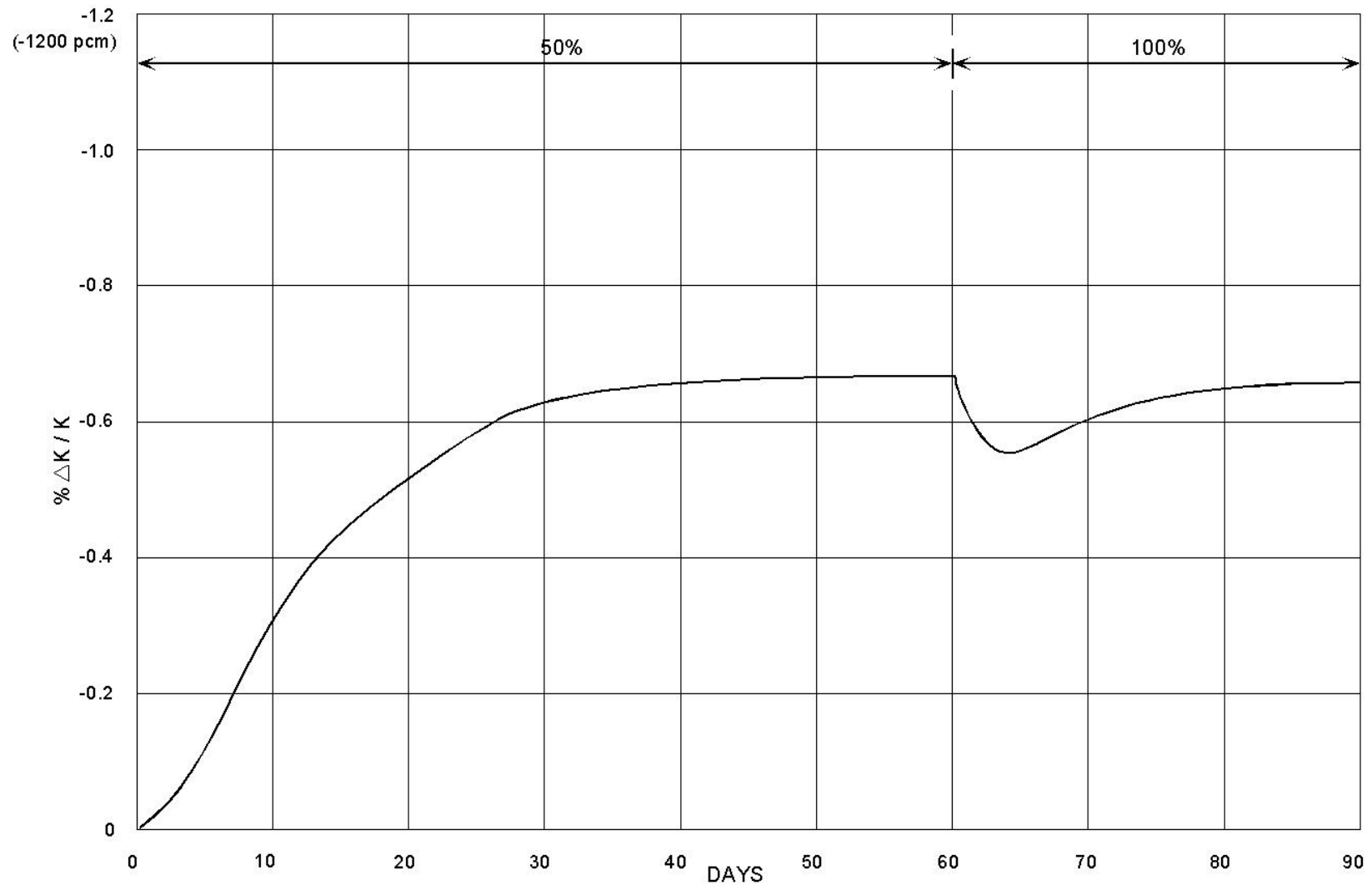


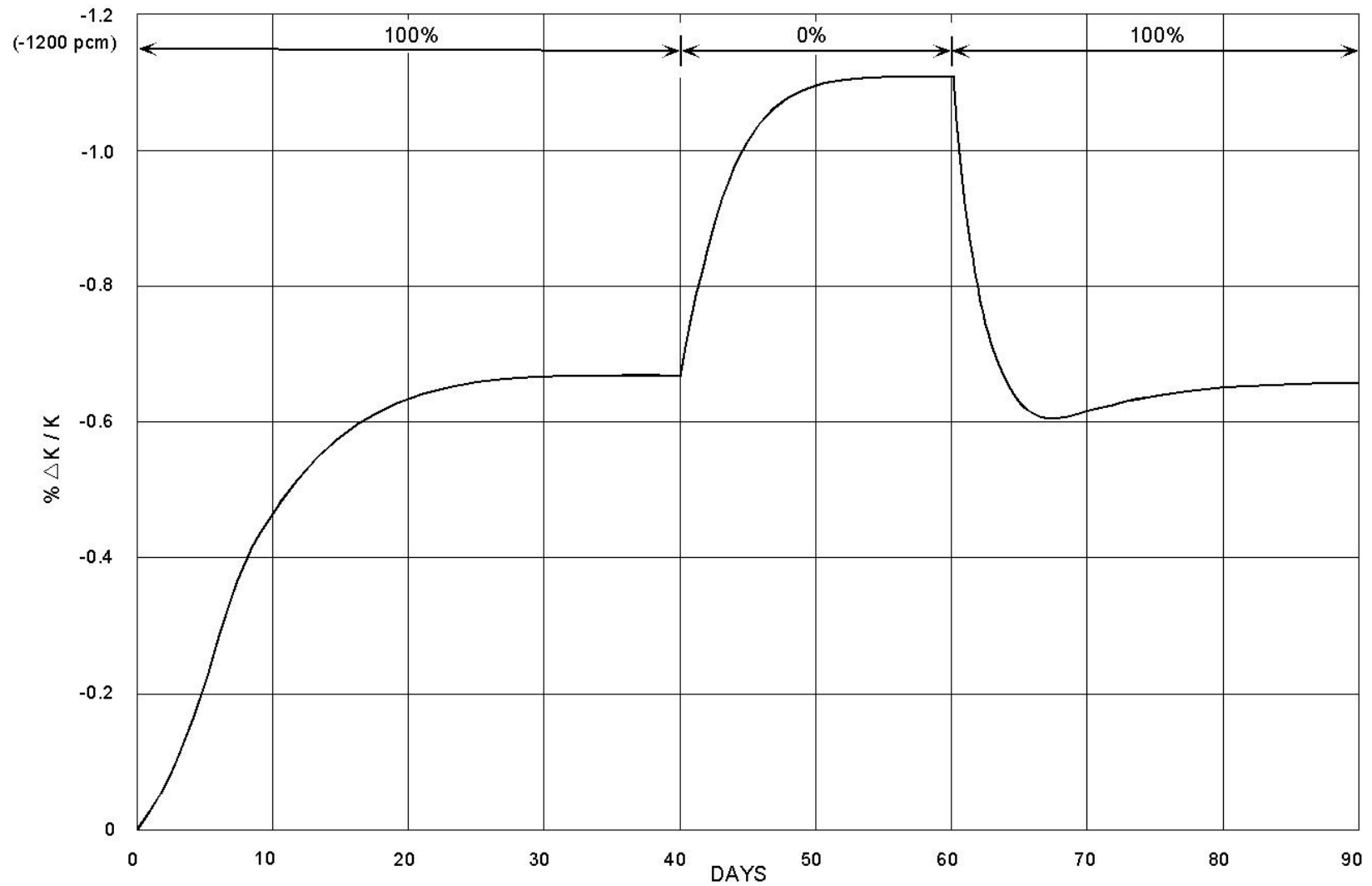
Figure 2.1-17 Samarium Transients Starting with a Clean Core



Samarium With Clean Core Fig 2.1-17



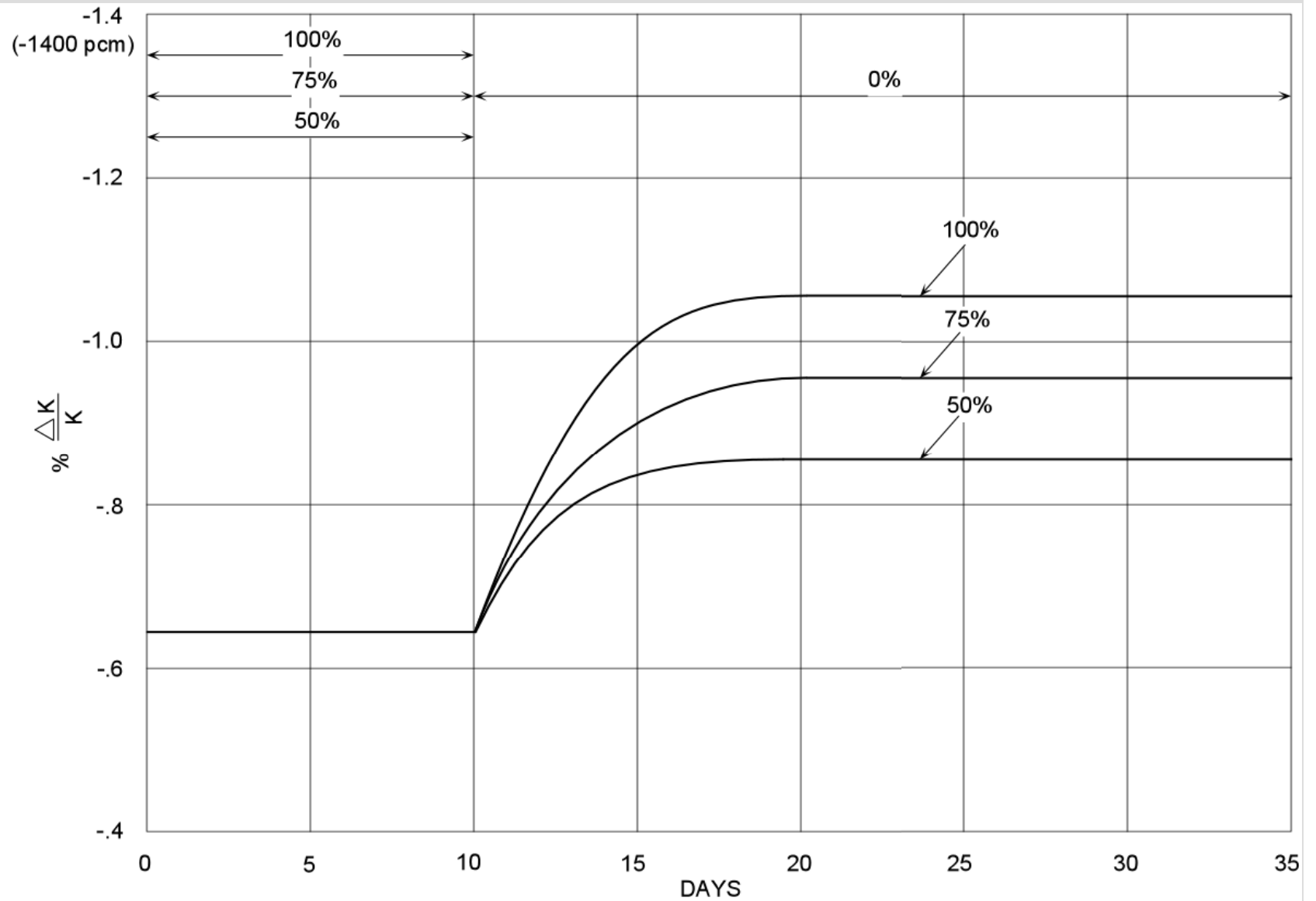
Figure 2.1-18 Samarium Transients Starting with a Clean Core



Post-Trip Samarium Fig 2.1-18



Figure 2.1-19 Samarium Shutdown Transients



Post-Trip Samarium (cont'd) Fig 2.1-19



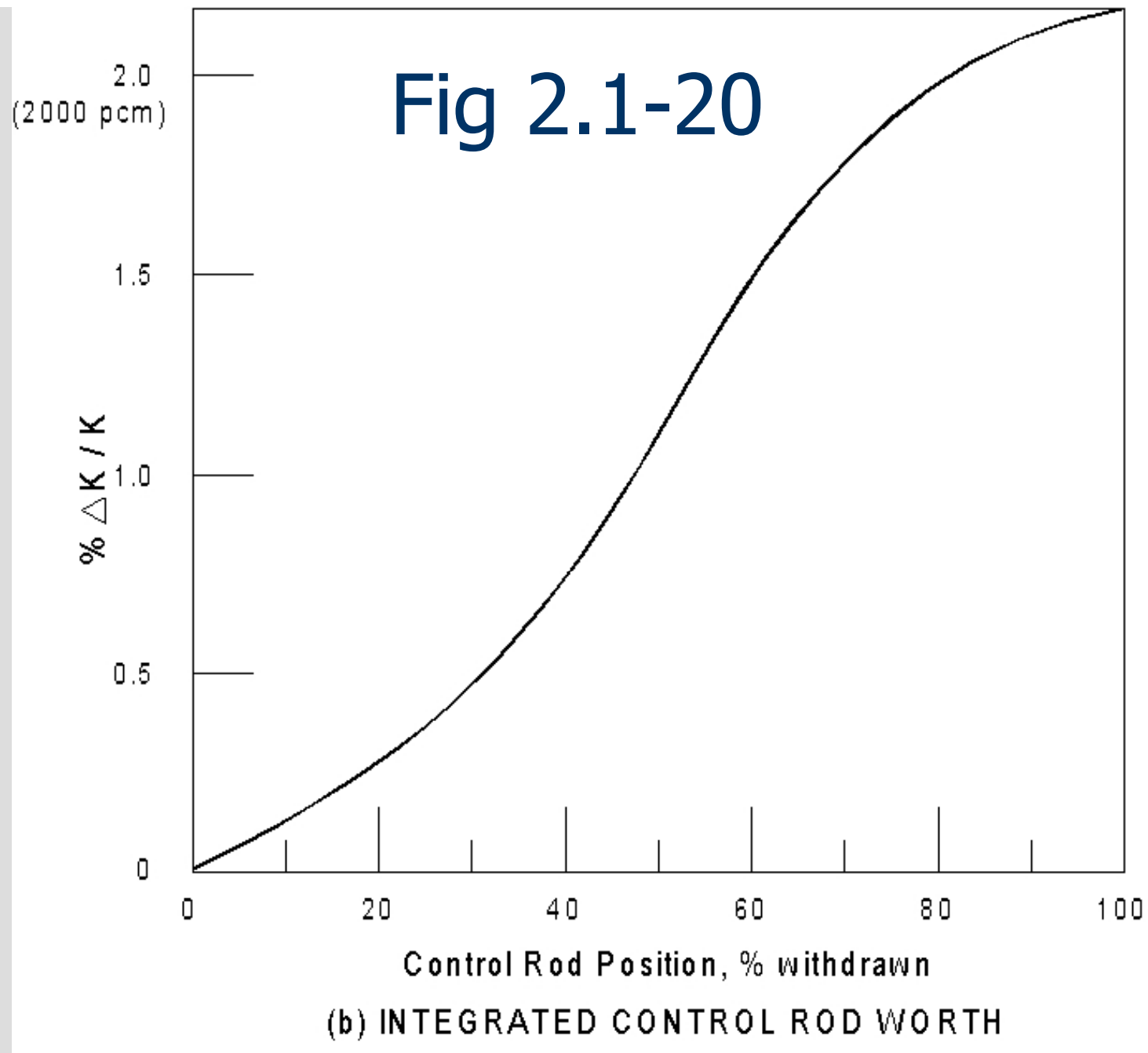


Control Rods



- Control rods absorb neutrons.
- Insert rods into core, - reactivity.
- Withdraw rods from core, + reactivity.
- Control rods affect the thermal utilization factor (f).



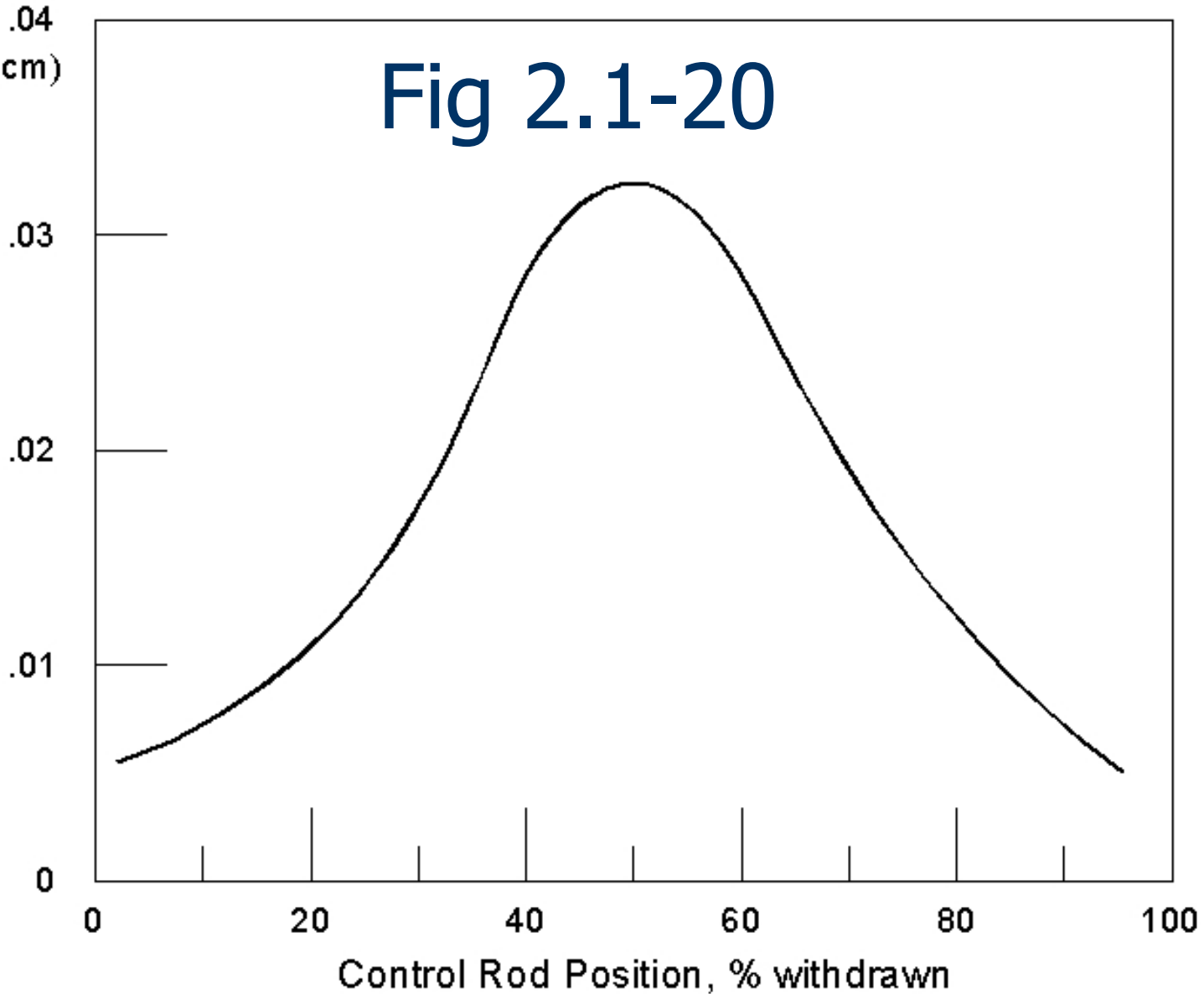




.04
(40 pcm)

Fig 2.1-20

% $\Delta K / K$ / % withdrawn



(a) DIFFERENTIAL CONTROL ROD WORTH





Chemical Shim



- Boron-10 has a very large absorption cross section for thermal neutrons: 3813 barns.
- Add boron, - reactivity.
- Remove boron (dilute), + reactivity.
- Boron affects thermal utilization factor (f).





Excess Reactivity



- This term is used to express the positive reactivity associated with the fuel.
- Excess reactivity is required to:
 - Overcome the power defect to allow operations at 100% power.
 - Overcome the negative reactivity added by fission product poisons.
 - Allow operation at 100% power for the design core lifetime.





Prompt Neutron Lifetime



- Time from neutron absorption to fission & neutron release = 10^{-14} sec
- Neutron release to absorption = 10^{-4} sec
- 10^{-14} sec + 10^{-4} sec $\sim 10^{-4}$ sec
- On prompt neutrons alone, time between each neutron generation is $\sim 10^{-4}$ sec
- This would make power increase very rapidly and make the reactor uncontrollable.





Delayed Neutrons



- As previously discussed, some of the fission products decay by neutron emission.
- 0.65% of all neutrons in the reactor are delayed neutrons. This delayed neutron fraction is called beta (β).





Delayed Neutron Lifetime



(continued)

- With prompt & delayed neutrons, each generation is about 0.1 seconds.
- The delayed neutrons make power increase more slowly and make the reactor controllable.
- β is the symbol for delayed neutron fraction.





Startup Rate



- **Startup Rate** (SUR) is the rate of change of reactor power in decades per minute.





Power Equation with SUR



$$P = P_0 10^{SUR(t)}$$

Where:

P = Final power

P₀ = Original power

SUR = Startup rate in
decades per minute

t = time in minutes





Startup Rate

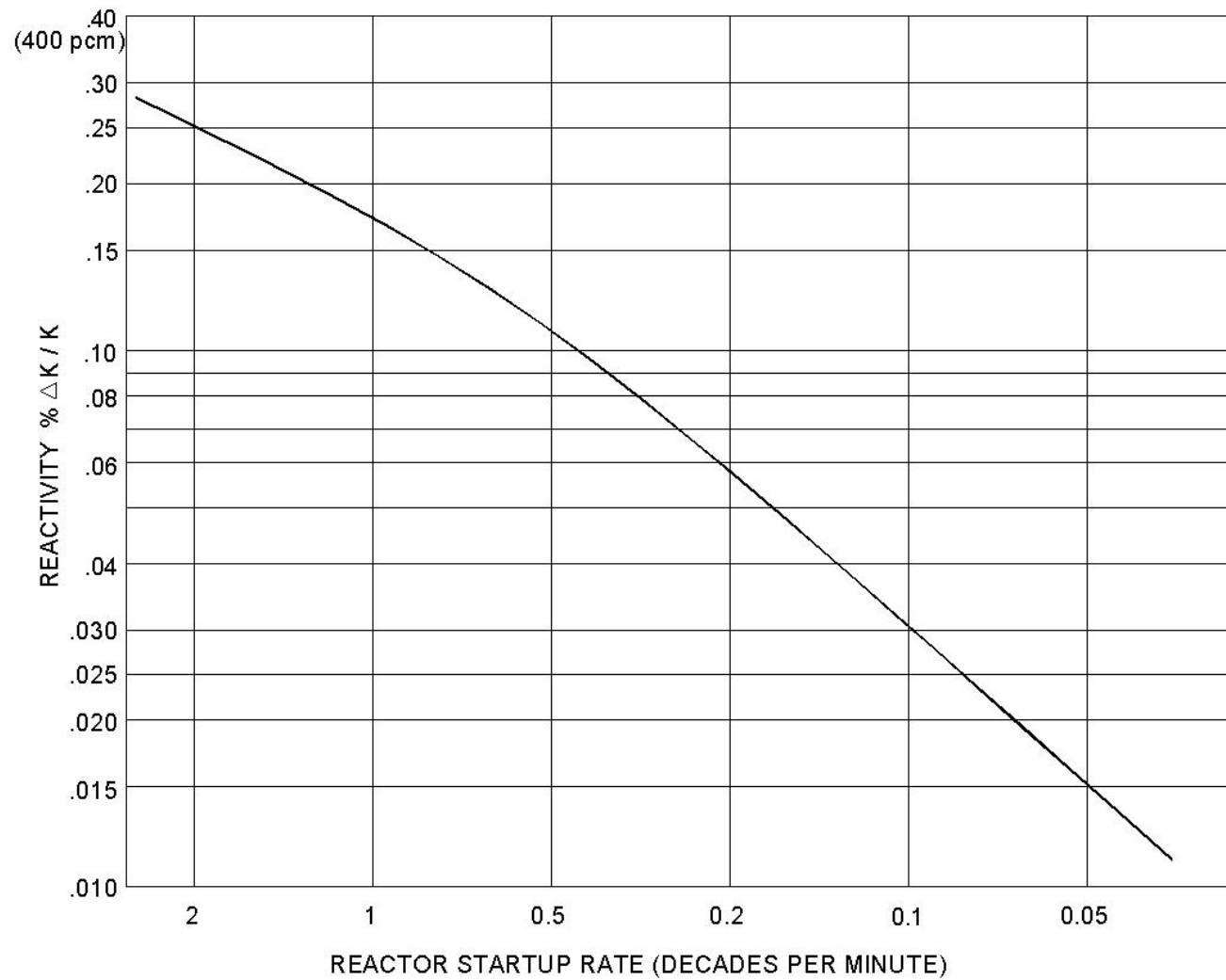


$$SUR = \frac{26.06 \lambda \rho}{\beta - \rho}, \rho \ll \beta$$

The transient response of the reactor is determined by the delayed neutron fraction and reactivity.



Figure 2.1-21 Reactivity versus Startup Rate



Reactivity vs SUR Fig 2.1-21





In a PWR above the point of adding heat, if the moderator temperature coefficient is negative, reactor power inherently follows secondary power.

