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. $K_{effective}$
    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* ----->

FP_1 + FP_2 + 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.

Instantaneous Energy Release	MeV/fission
K.E. of fission fragments	165
Prompt γ energy	5
Capture γ energy	5
K.E. of prompt neutrons	7
Total	182

Delayed Energy Release	
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 ~ 99.35% of total number of neutrons asociated with the fissioning of a U-235 nucleus.

Delayed Neutrons

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

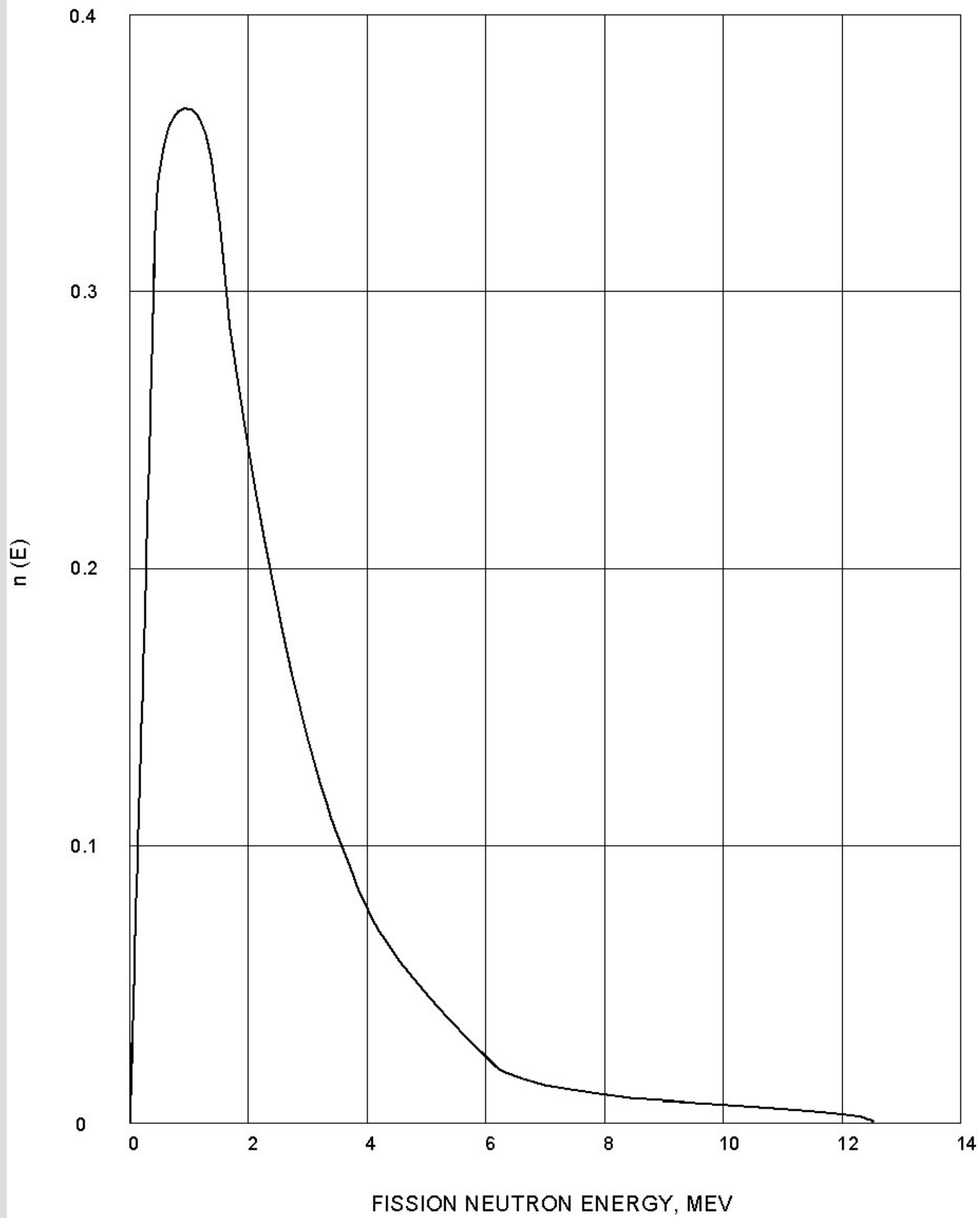
Neutron Cross Section

- 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

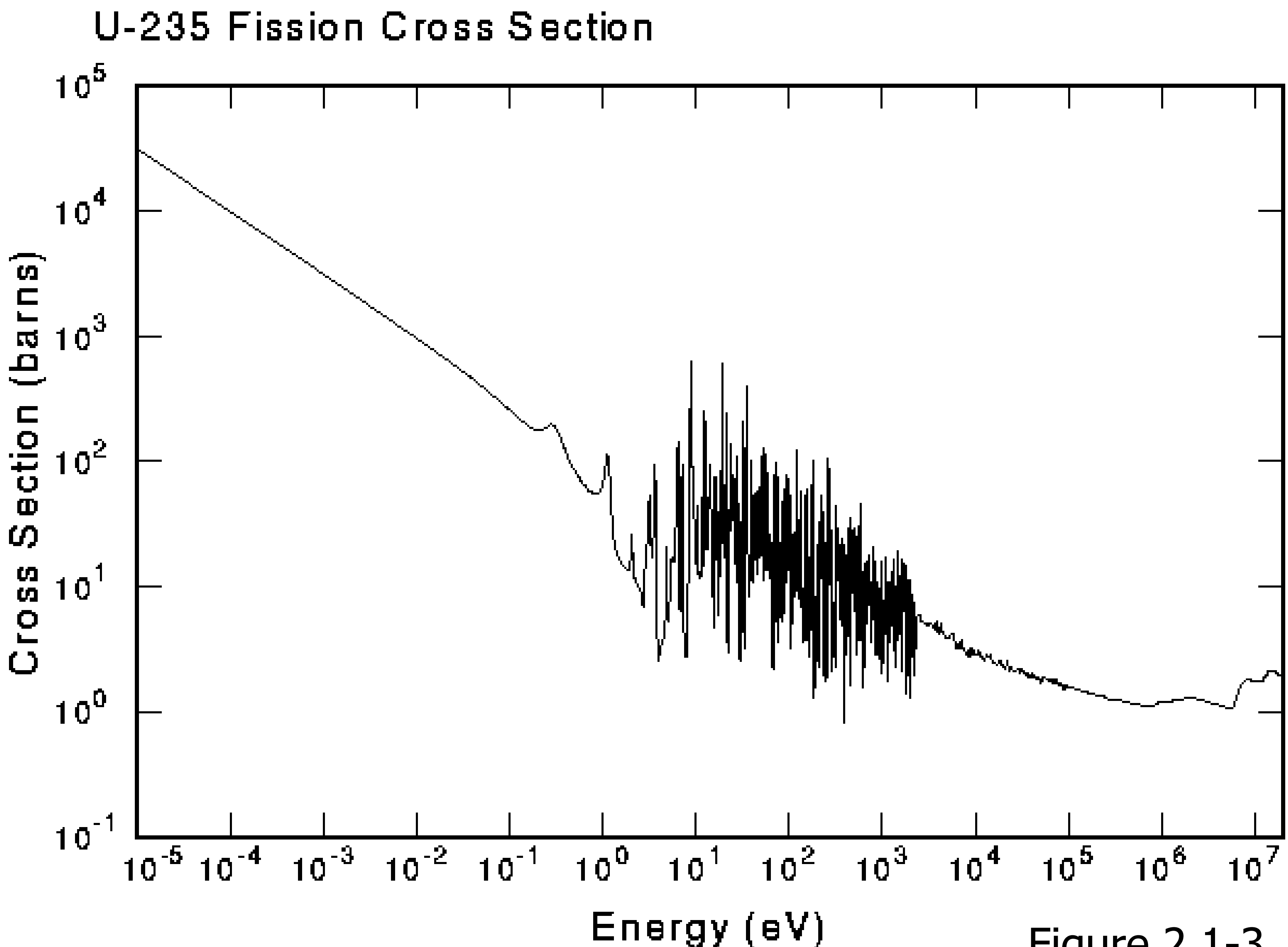

U-235 Fission Cross Section
Cross Section (barns)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
Energy (eV)

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:

    $$^{115}_{49}In + ^{1}_{0}n \rightarrow ^{116}_{49}In^{*} \rightarrow ^{116}_{49}In + ^{0}_{0}\gamma$$

    Charged particle emission:

    $$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}\alpha$$

  - 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

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

or

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

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

Six Factor Formula

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

Where:

$\varepsilon (epsilon) = fast\ fission\ factor$

$L_f = fast\ nonleakage\ factor$

$p = resonance\ escape\ probability$

$L_{th} = thermal\ nonleakage\ factor$

$f = thermal\ utilization\ factor$

$\eta (eta) = neutron\ production\ factor$

$K_{effective}$

- If $N=N_0$, the reaction is self-sustaining. $K_{eff}=1$, and the reactor is critical.

- If $N<N_0$, neutron population is decreasing. $K_{eff}<1$, and the reactor is subcritical.

- If $N>N_0$, neutron population is increasing. $K_{eff}>1$, 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

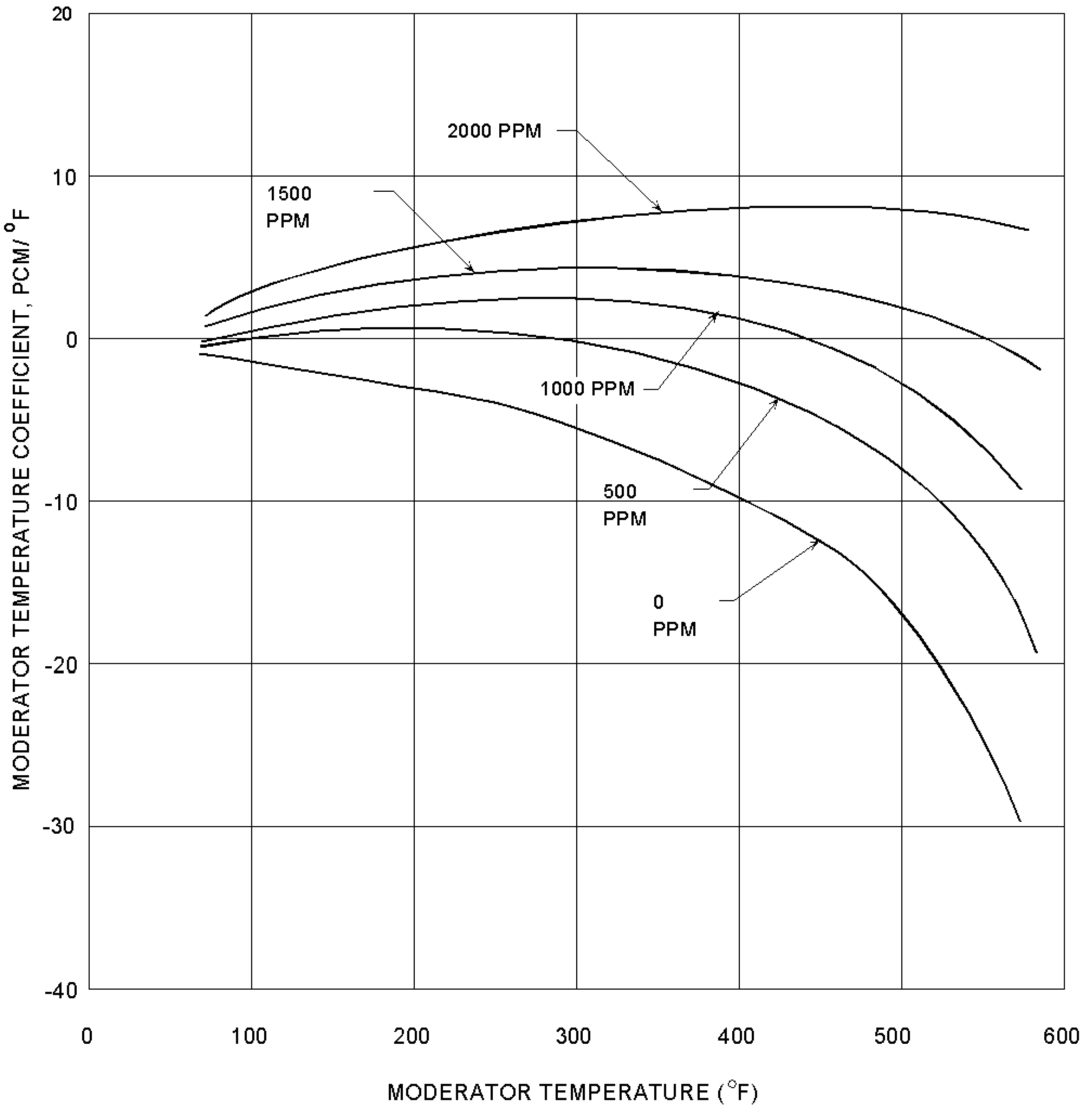
- $\frac{\Delta K}{K}$, $\%\frac{\Delta K}{K}$, and pcm.
- $1\ \frac{\Delta K}{K} = 100\ \%\frac{\Delta K}{K} = 10^5$ pcm
- $\%\frac{\Delta K}{K}$ Used in Technical Specifications
- Percent millirho (pcm), used by Westinghouse

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 ~0.5%.
- Changes from -30 pcm/%void at BOL & low temperatures to -250 pcm/%void at EOL & operating temperatures.
- This coefficient only has a significant effect in accidents.

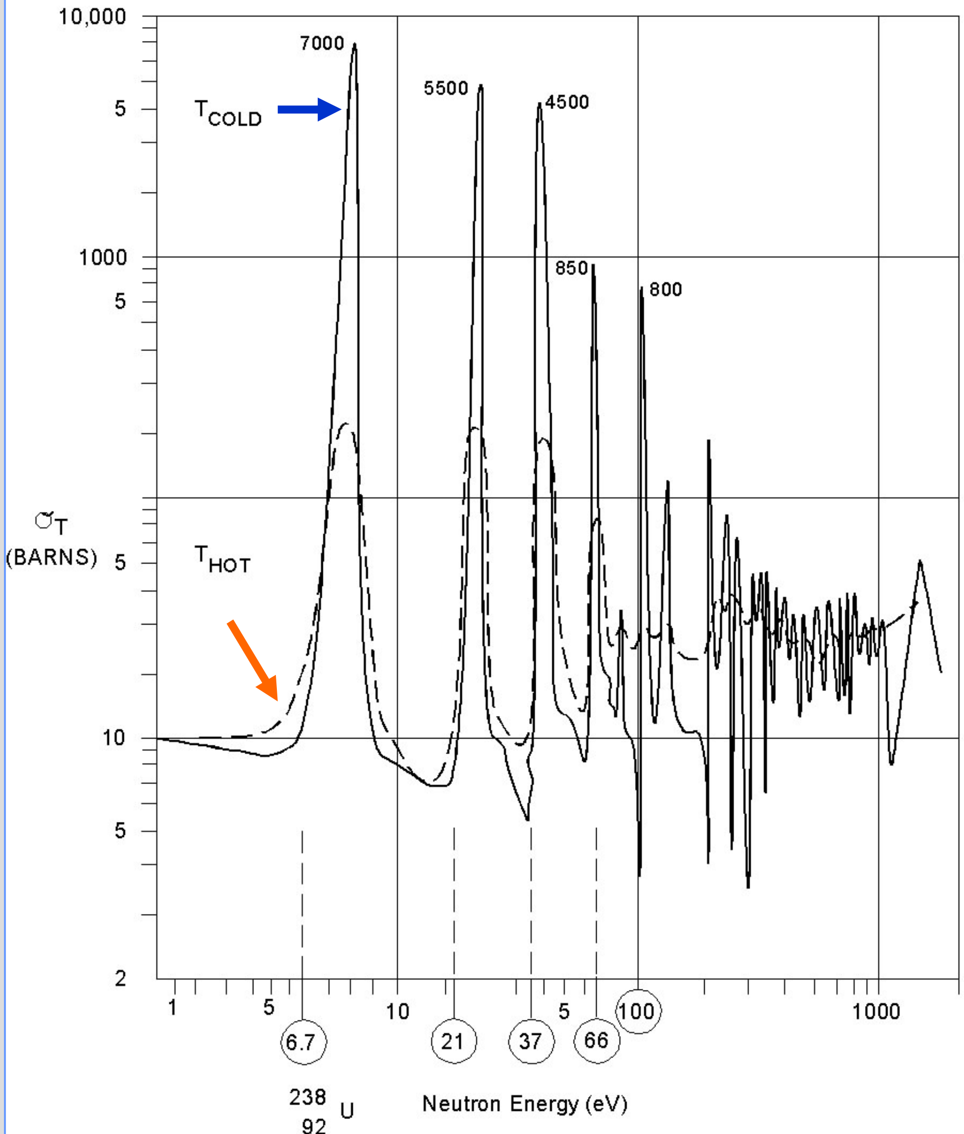
Pressure Coefficient

- 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.

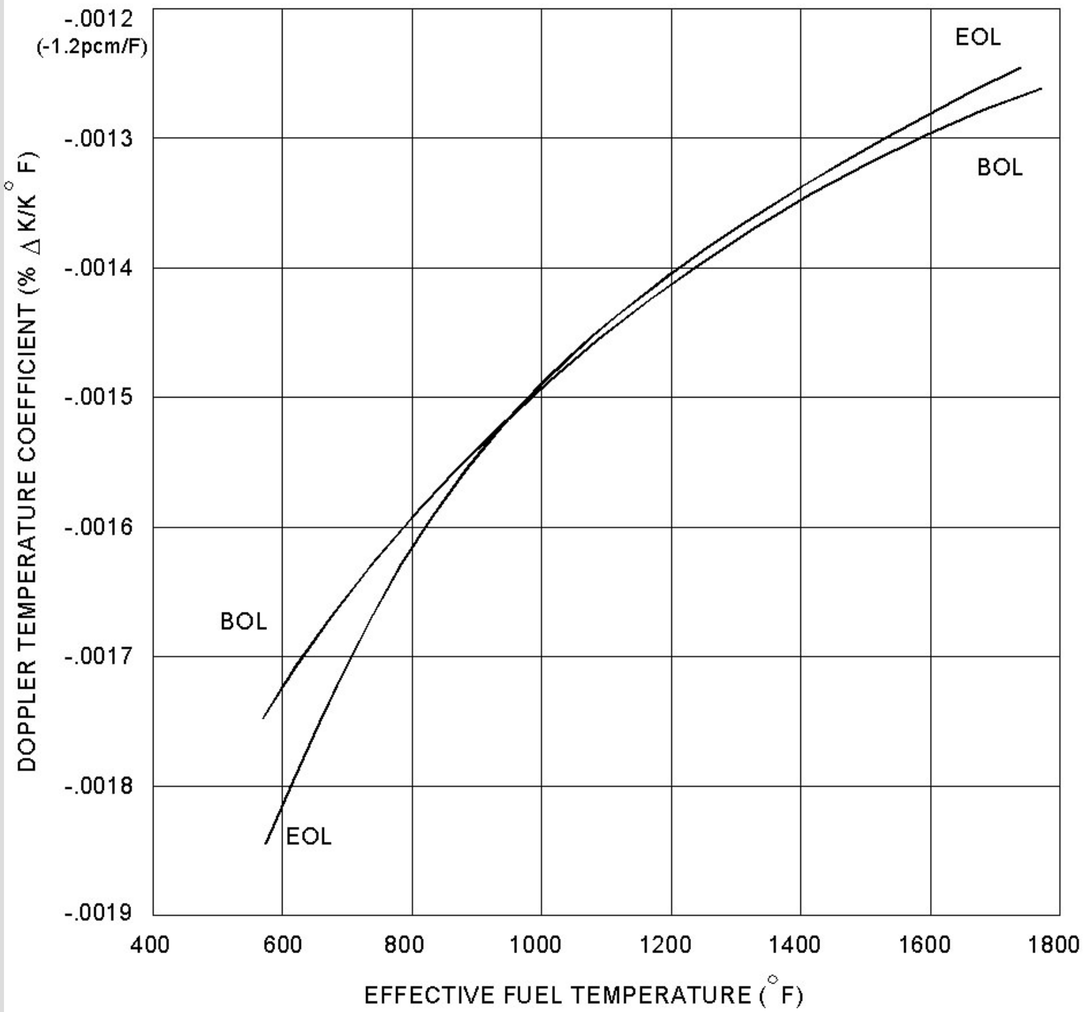
- It is brought about by the nature of some fuel materials, principally U-238 and Pu-240.



Cross Section Curve

Fig 2.1-4

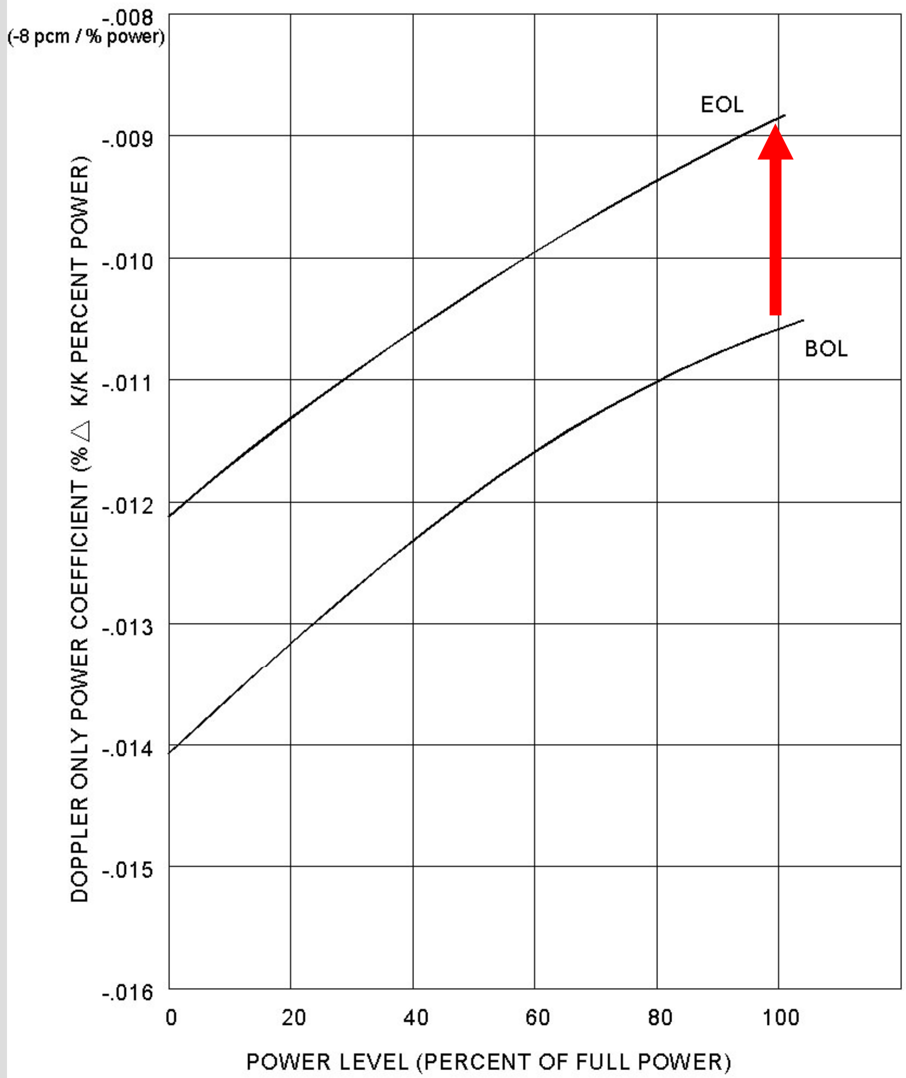
Figure 2.1-4 Cross Section Curve



Fuel Temp Coefficient

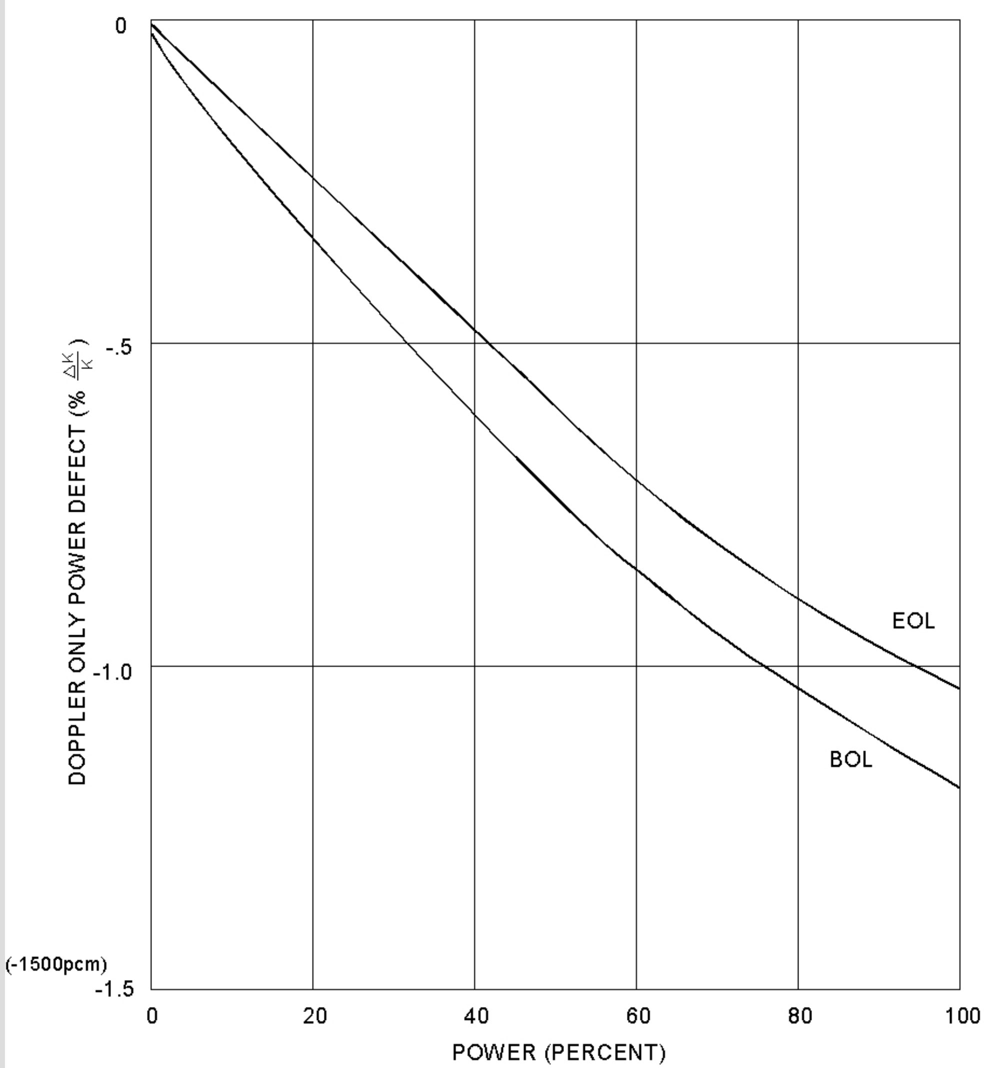
Fig 2.1-5

Figure 2.1-5 Doppler Temperature Coefficient, BOL and EOL



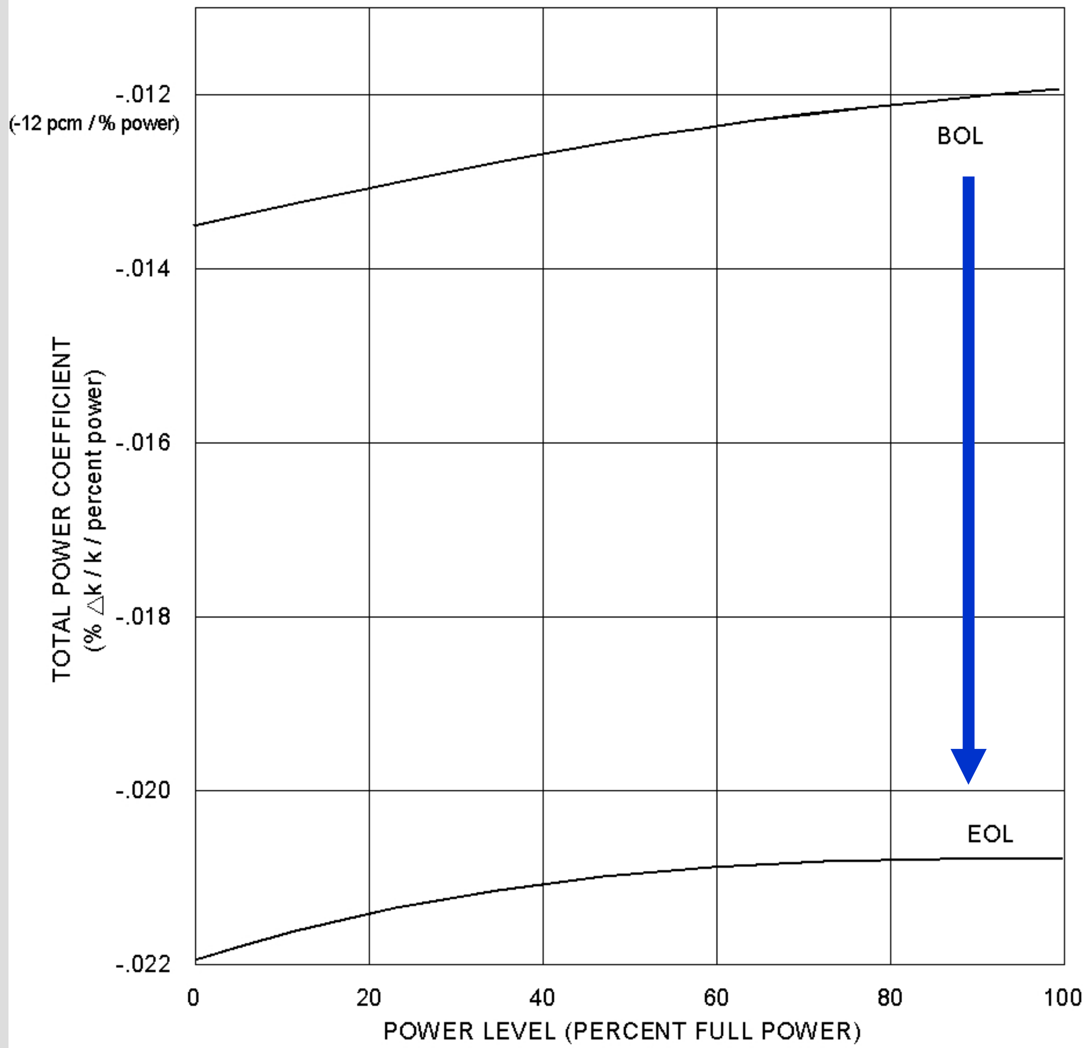
Doppler-Only Power Coefficient Fig 2.1-6

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



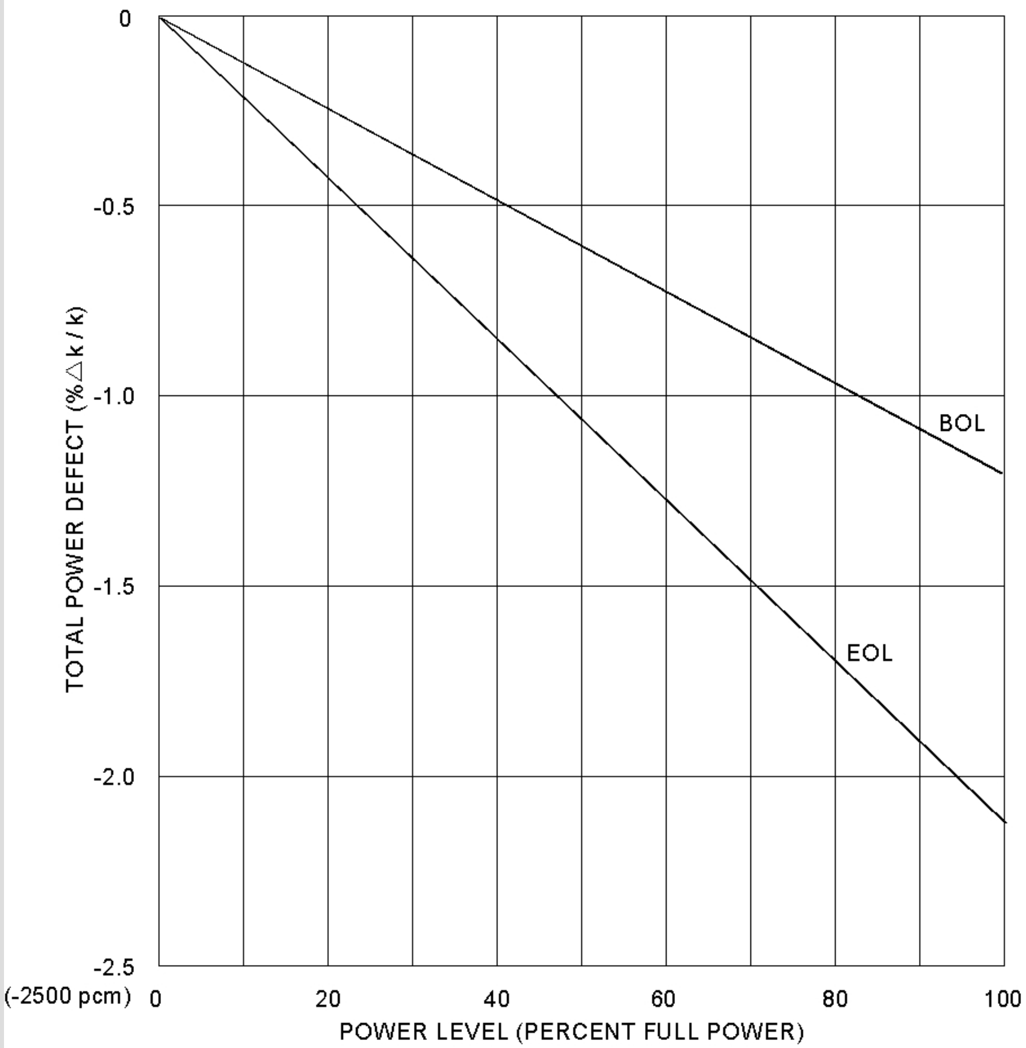
Doppler-Only Power Defect
Fig 2.1-7

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.

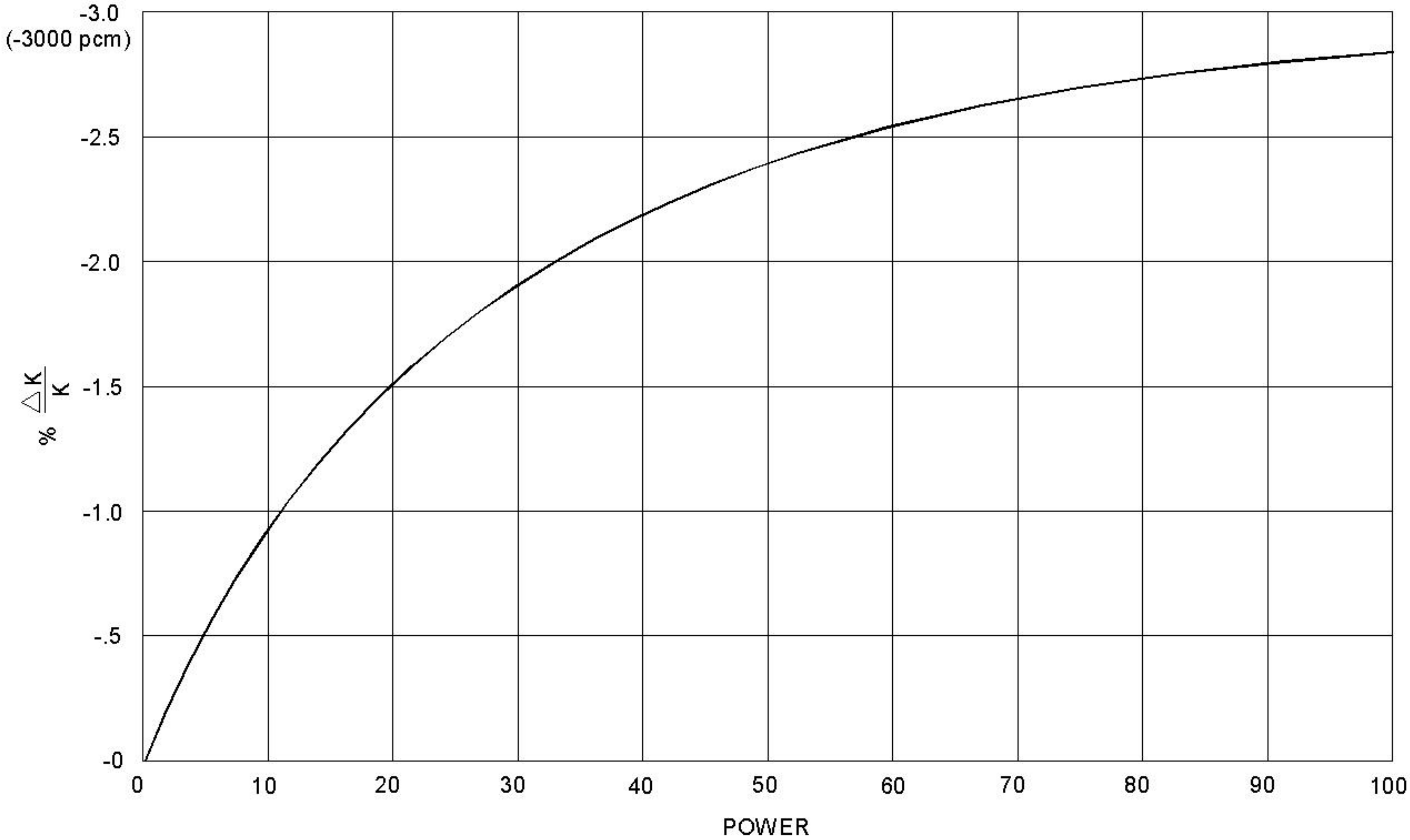


Figure 2.1-12 Equilibrium Xenon Worth vs Percent of Full Power

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Equilibrium Xenon vs Power Fig 2.1-12

Xenon Buildup

- Xenon production:

  Directly from fission (0.3% yield)

  Decay of Tellurium (5.9% yield)

$$^{135}_{52}Te \rightarrow \, ^{135}_{53}I + \, ^{0}_{-1}\beta \rightarrow \, ^{135}_{54}Xe + \, ^{0}_{-1}\beta$$

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

Xenon Removal

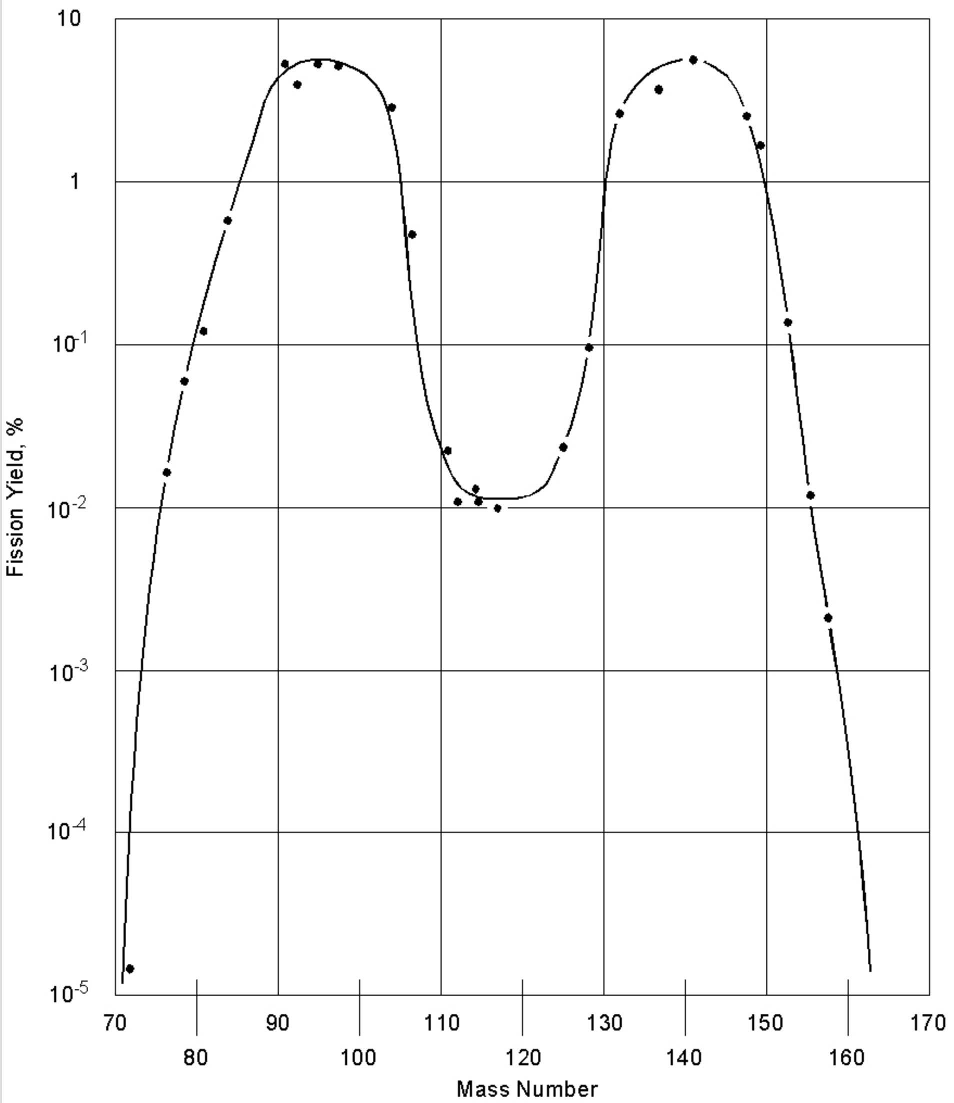
- Burnout

$$^{135}_{54}Xe + ^{1}_{0}n \rightarrow ^{136}_{54}Xe \quad (Stable)$$

- Decay

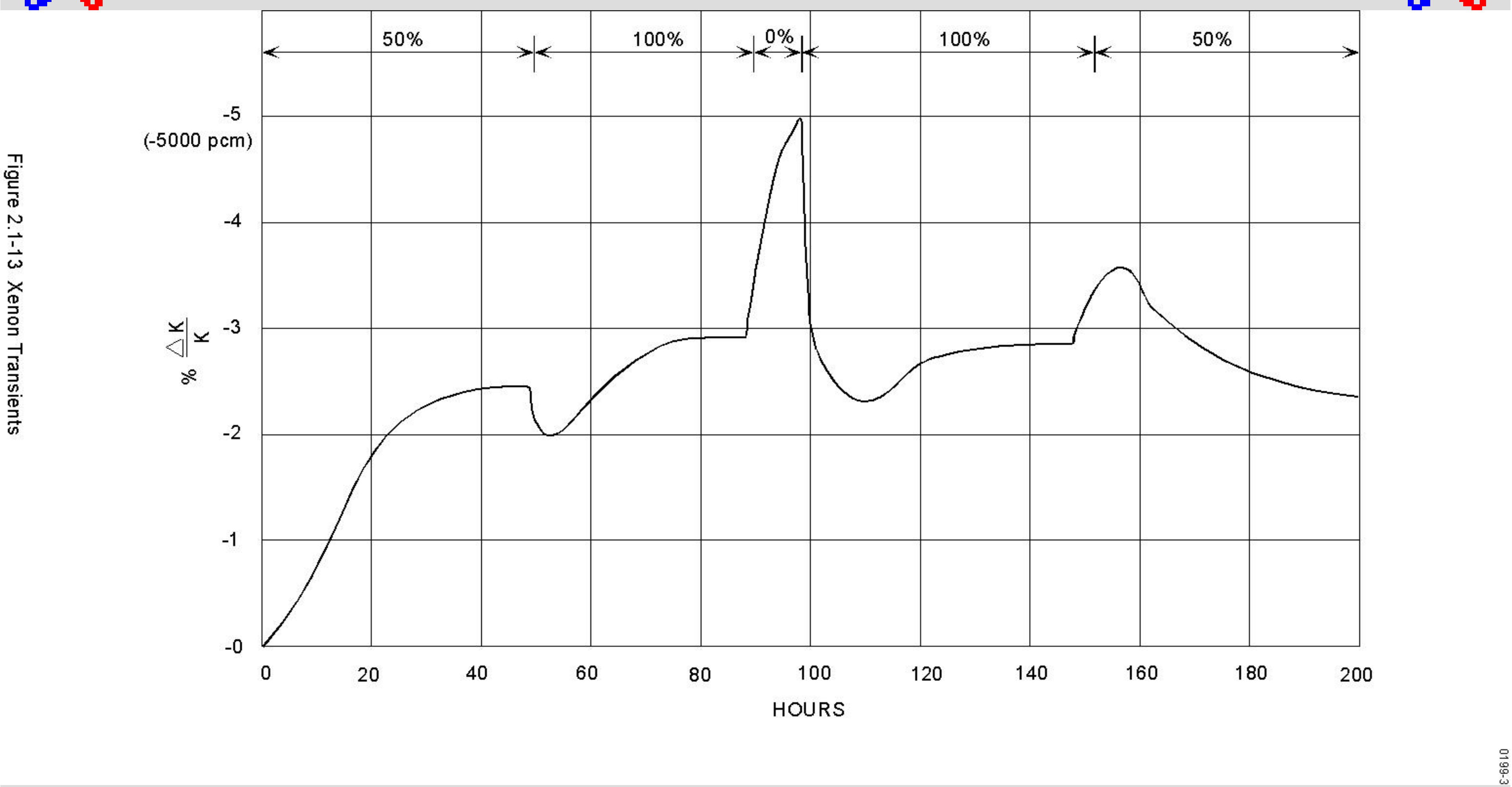
$$^{135}_{54}Xe \rightarrow ^{135}_{55}Cs + ^{0}_{-1}\beta \rightarrow ^{135}_{56}Ba + ^{0}_{-1}\beta$$

$$t_{\frac{1}{2}} = 9.2h \qquad t_{\frac{1}{2}} = 20000y$$



Fission Yield Fig 2.1-11

Figure 2.1-11 Fission Yield versus Mass Number



Xenon Transients Fig 2.1-13

Xe

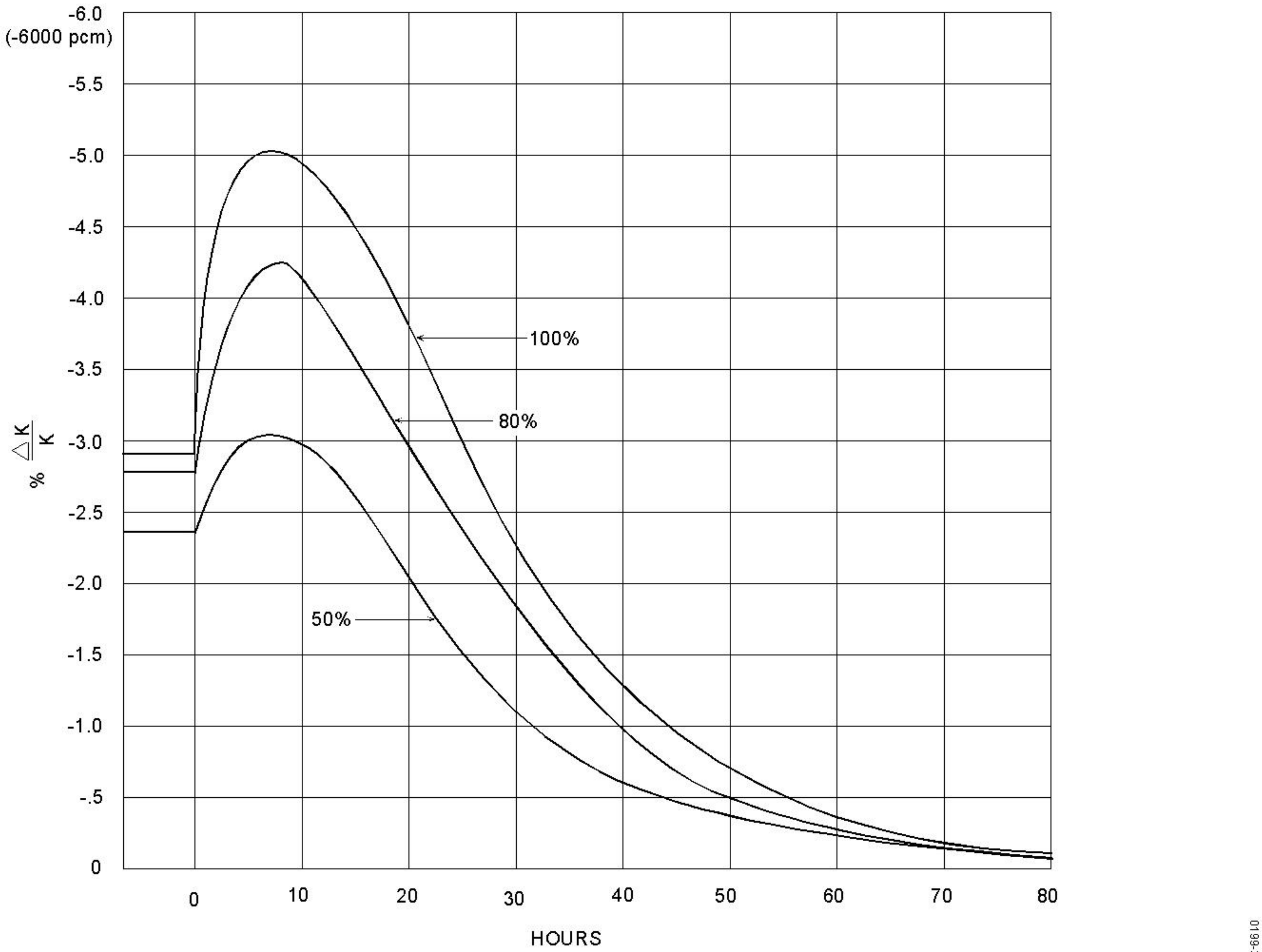
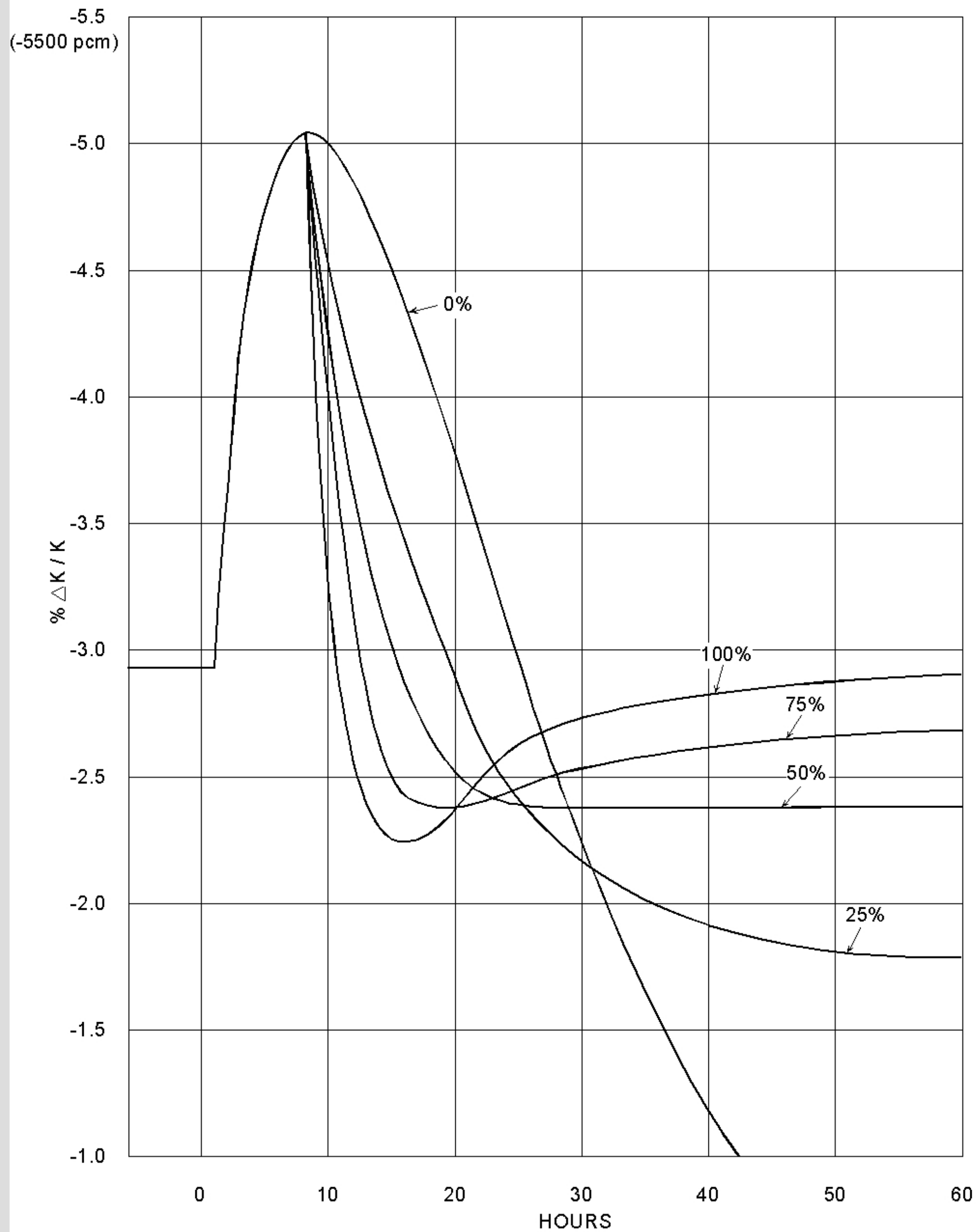


Figure 2.1-14 Xenon Transients Following a Reactor Trip

Post Trip Xenon Fig 2.1-14

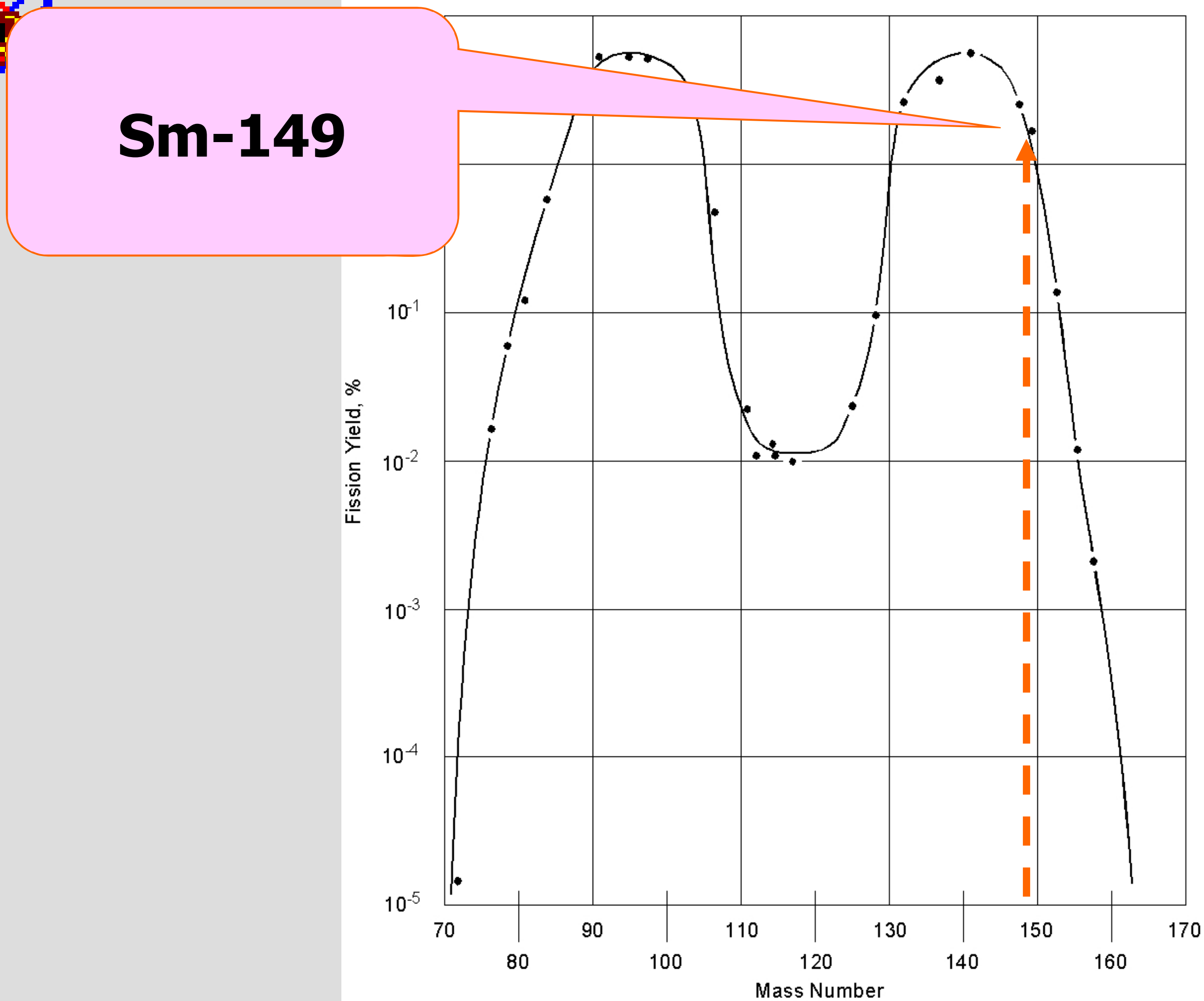


Xenon Transients Fig 2.1-15

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.



Fission Yield Fig 2.1-11

Figure 2.1-11 Fission Yield versus Mass Number

Samarium Production/Removal

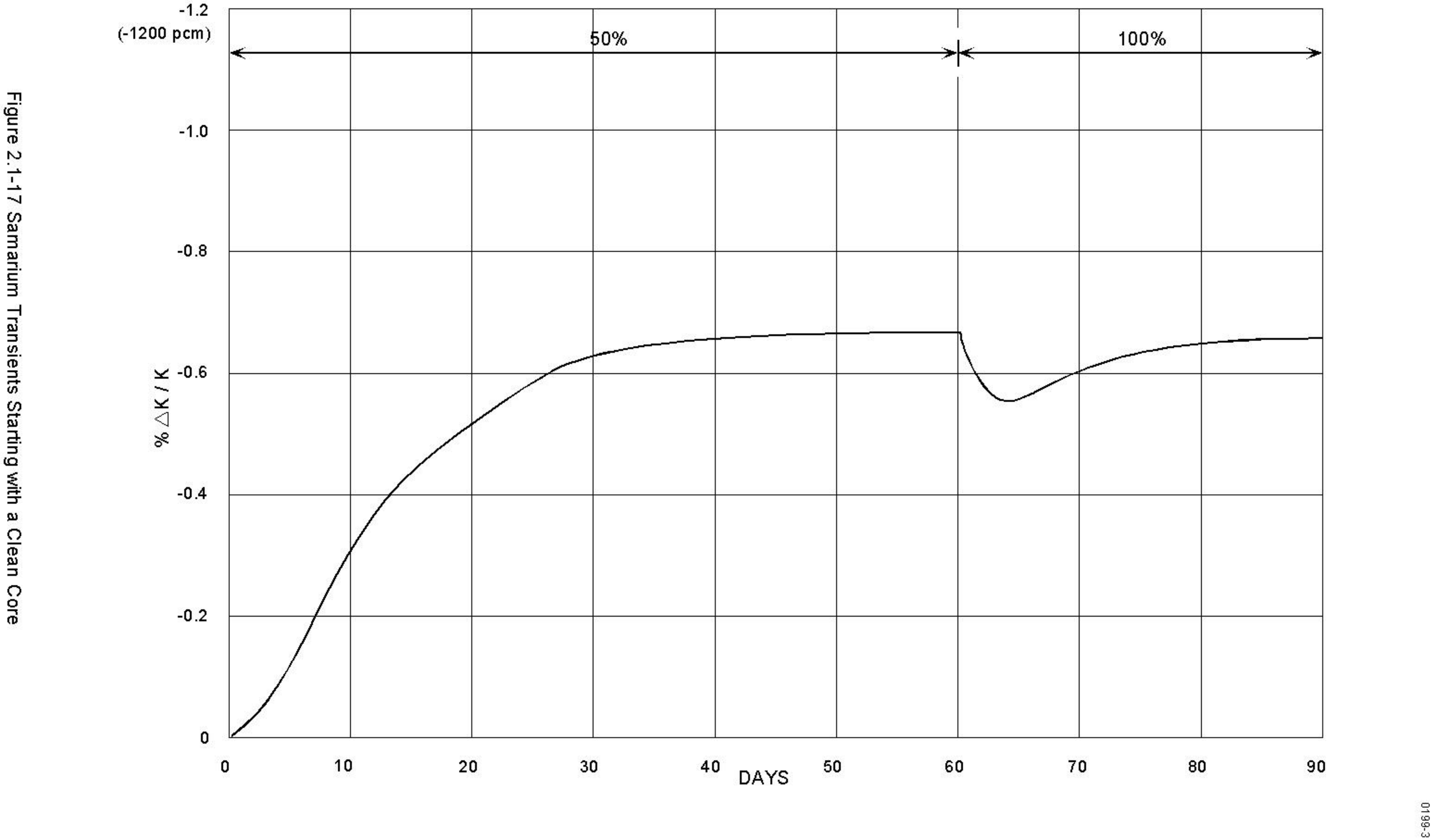
- Production

$$ {}^{149}_{60}Nd \rightarrow {}^{149}_{61}Pm + {}^{0}_{-1}\beta \rightarrow {}^{149}_{62}Sm \;\; (Stable) $$

$$ t_{\frac{1}{2}} = 1.7h \qquad\qquad t_{\frac{1}{2}} = 53h $$

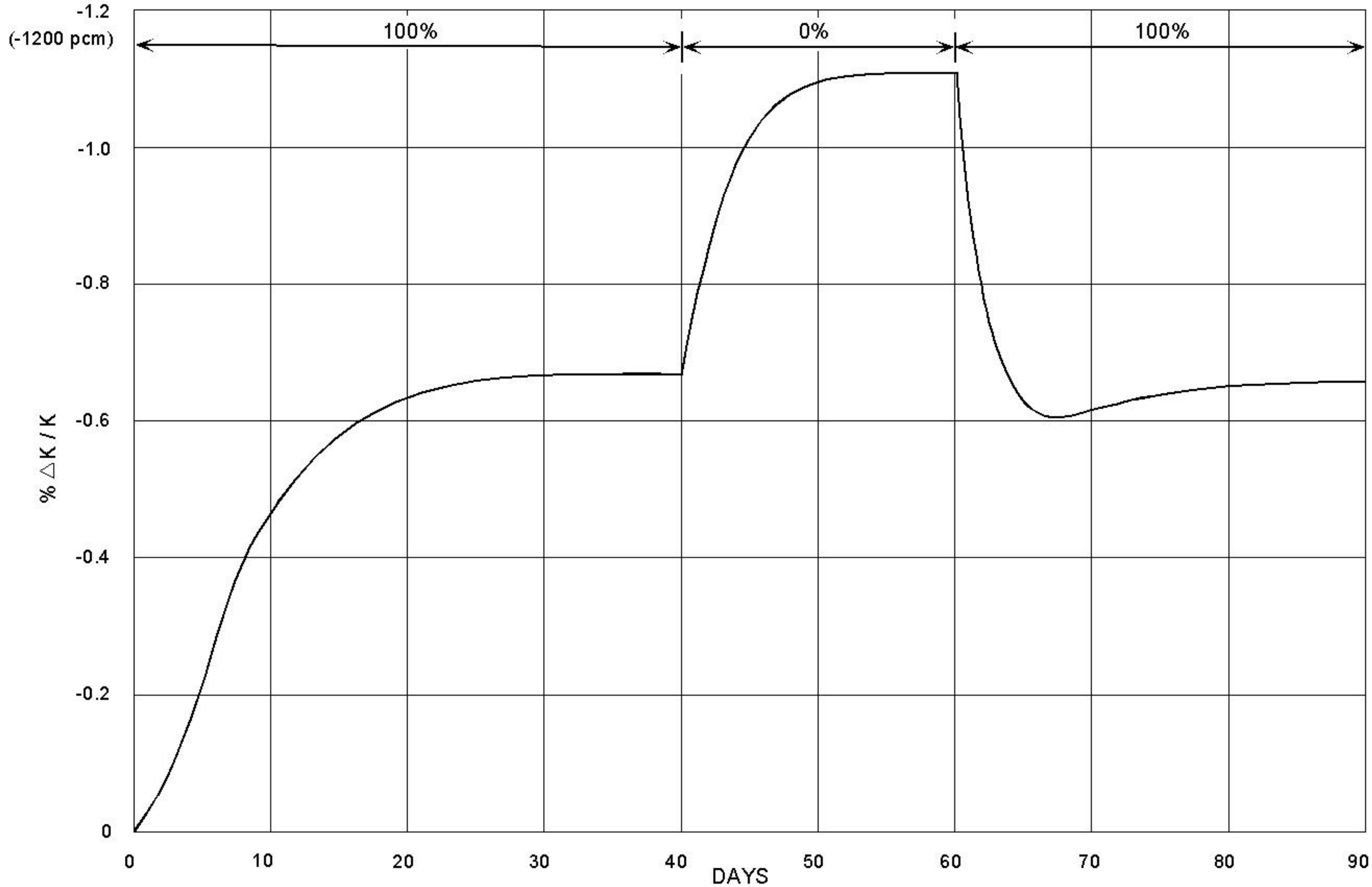
- Removal

$$ {}^{149}_{62}Sm + {}^{1}_{0}n \rightarrow {}^{150}_{62}Sm $$



Samarium With Clean Core Fig 2.1-17

Figure 2.1-18 Samarium Transients Starting with a Clean Core



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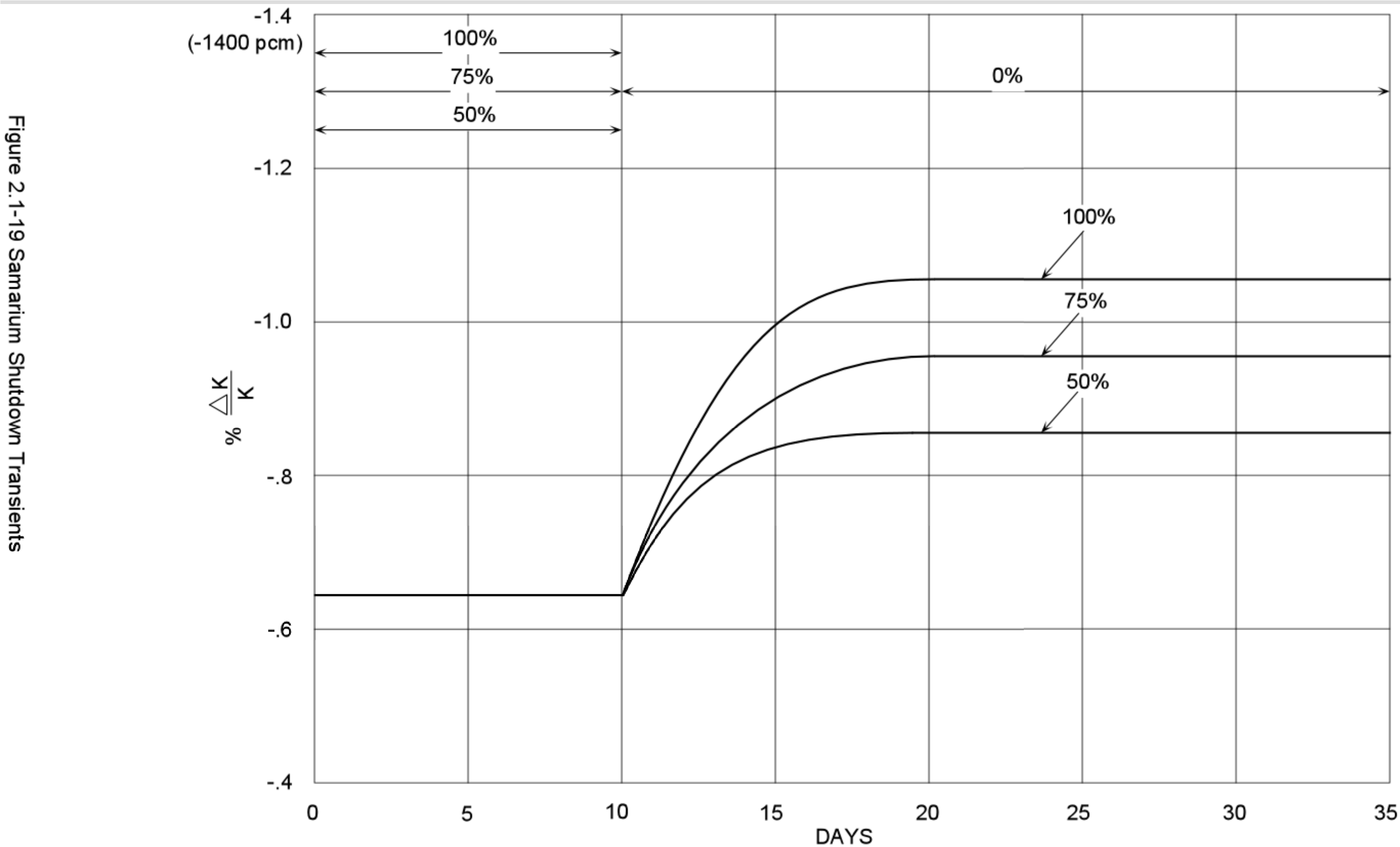
Post-Trip Samarium Fig 2.1-18

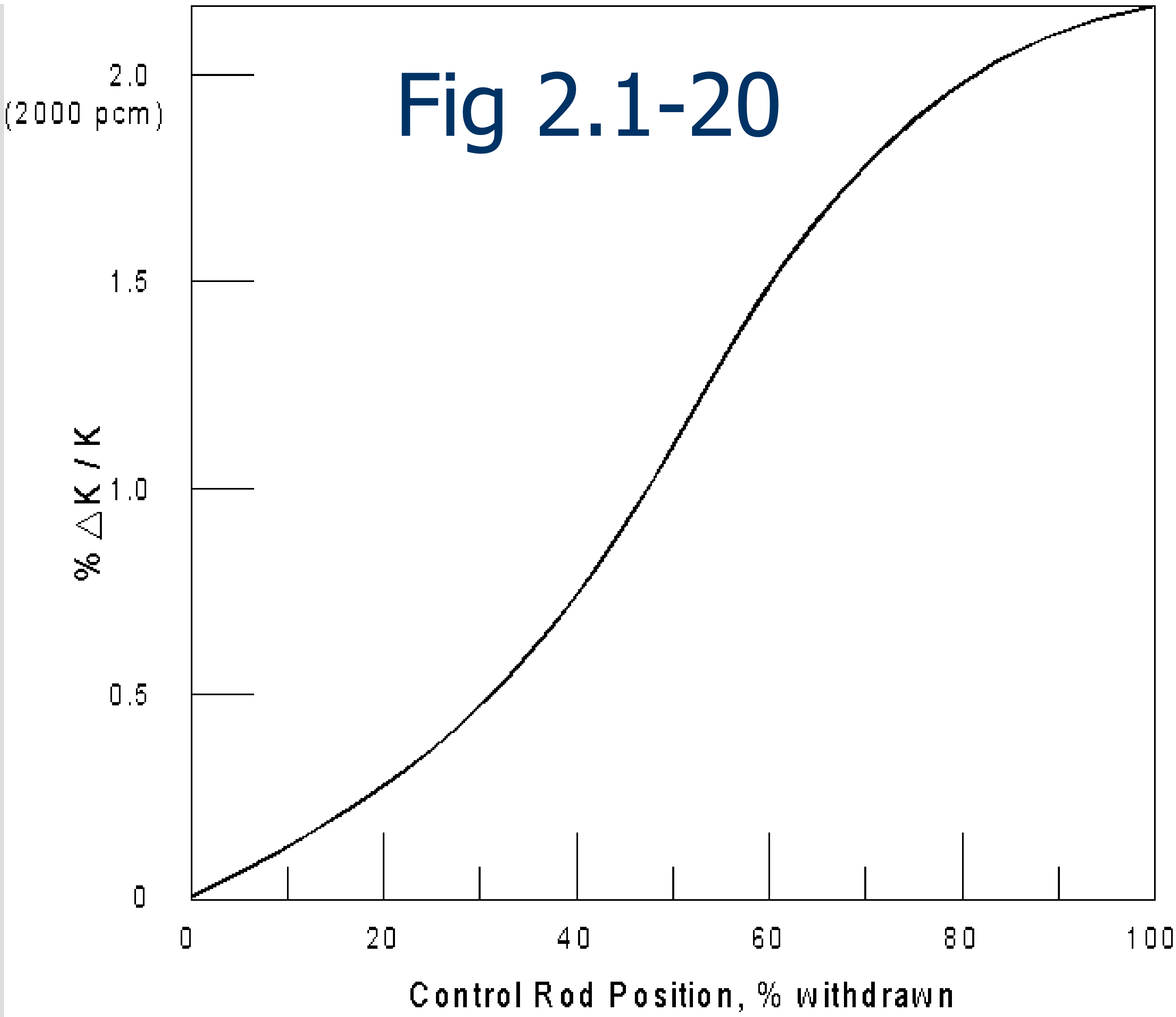


Post-Trip Samarium (cont'd) Fig 2.1-19

Control Rods

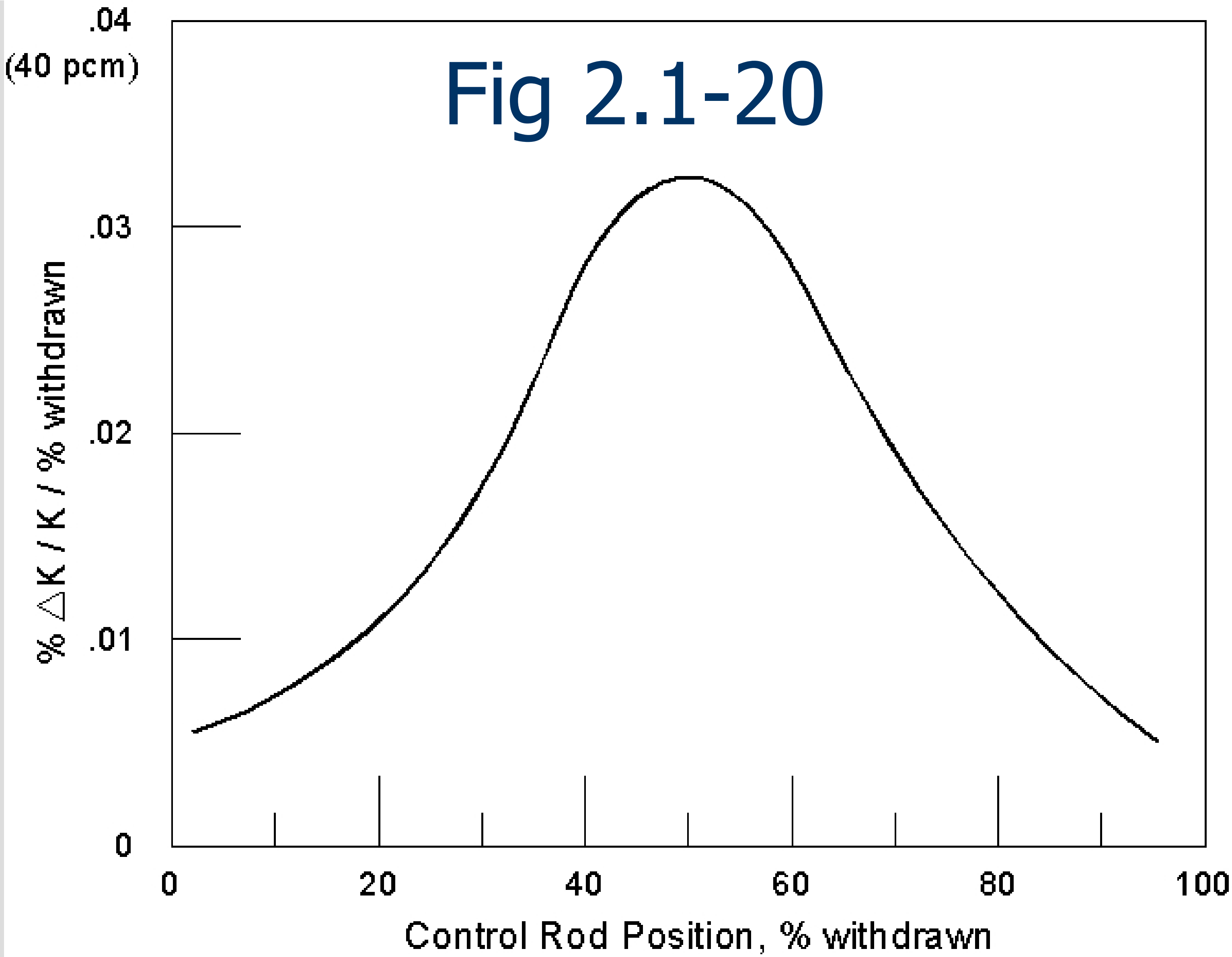
- Control rods absorb neutrons.
- Insert rods into core, - reactivity.
- Withdraw rods from core, + reactivity.
- Control rods affect the thermal utilization factor (f).

Fig 2.1-20



(b) INTEGRATED CONTROL ROD WORTH

Fig 2.1-20



(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 ~ 10^{-4} sec
- On prompt neutrons alone, time between each neutron generation is ~ 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

P_0 = Original power

SUR = Startup rate in decades per minute

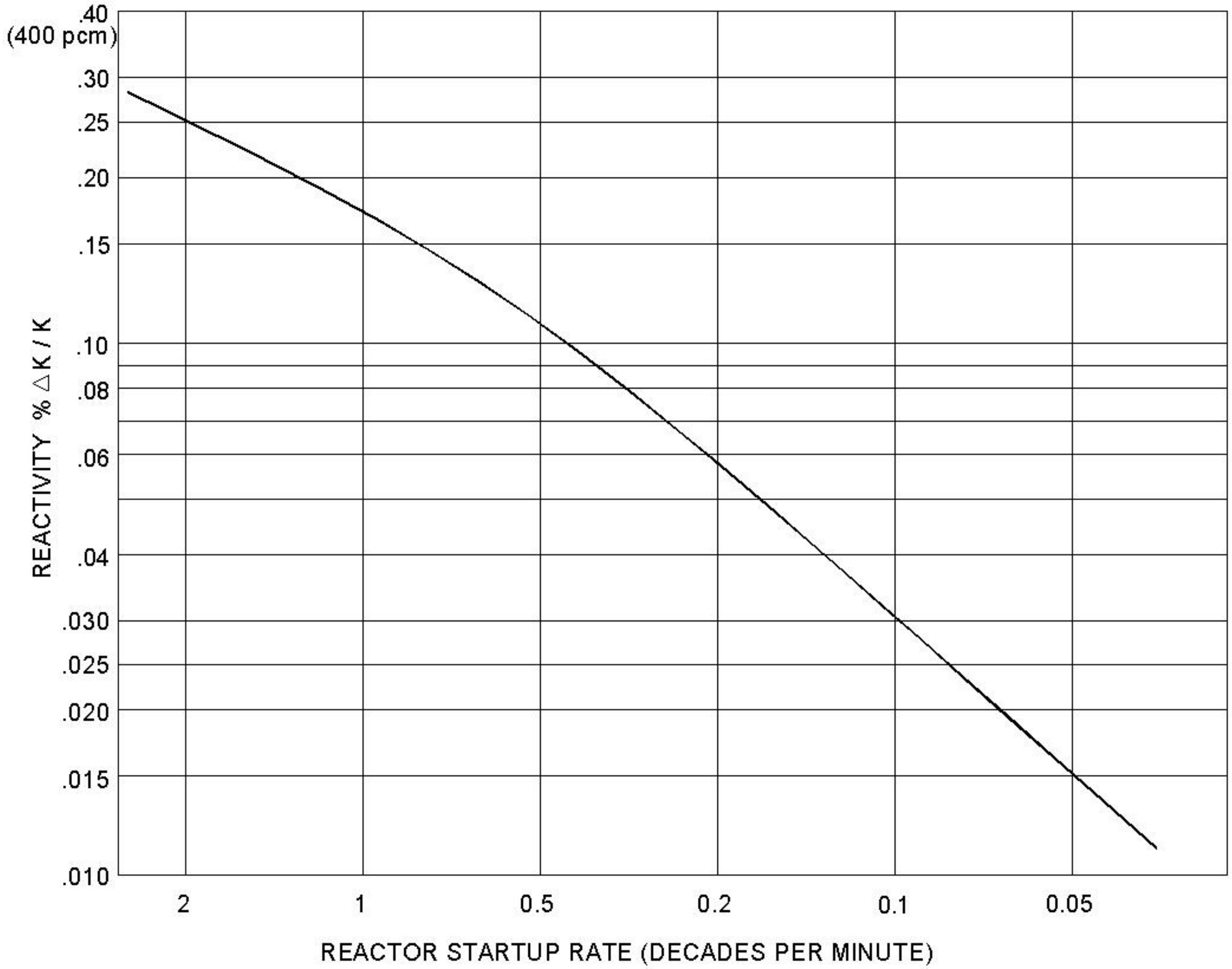
t = time in minutes

Startup Rate

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

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.