Operational Reactor Safety

22.091/22.903

Professor Andrew C. Kadak
Professor of the Practice

Lecture 4
Fuel Depletion & Related Effects

Topics to Be Covered

- Fuel "burnup"
- Transmutation
- Conversion/Breeding
- Samarium 149
- Xenon 135
- Operational Impacts

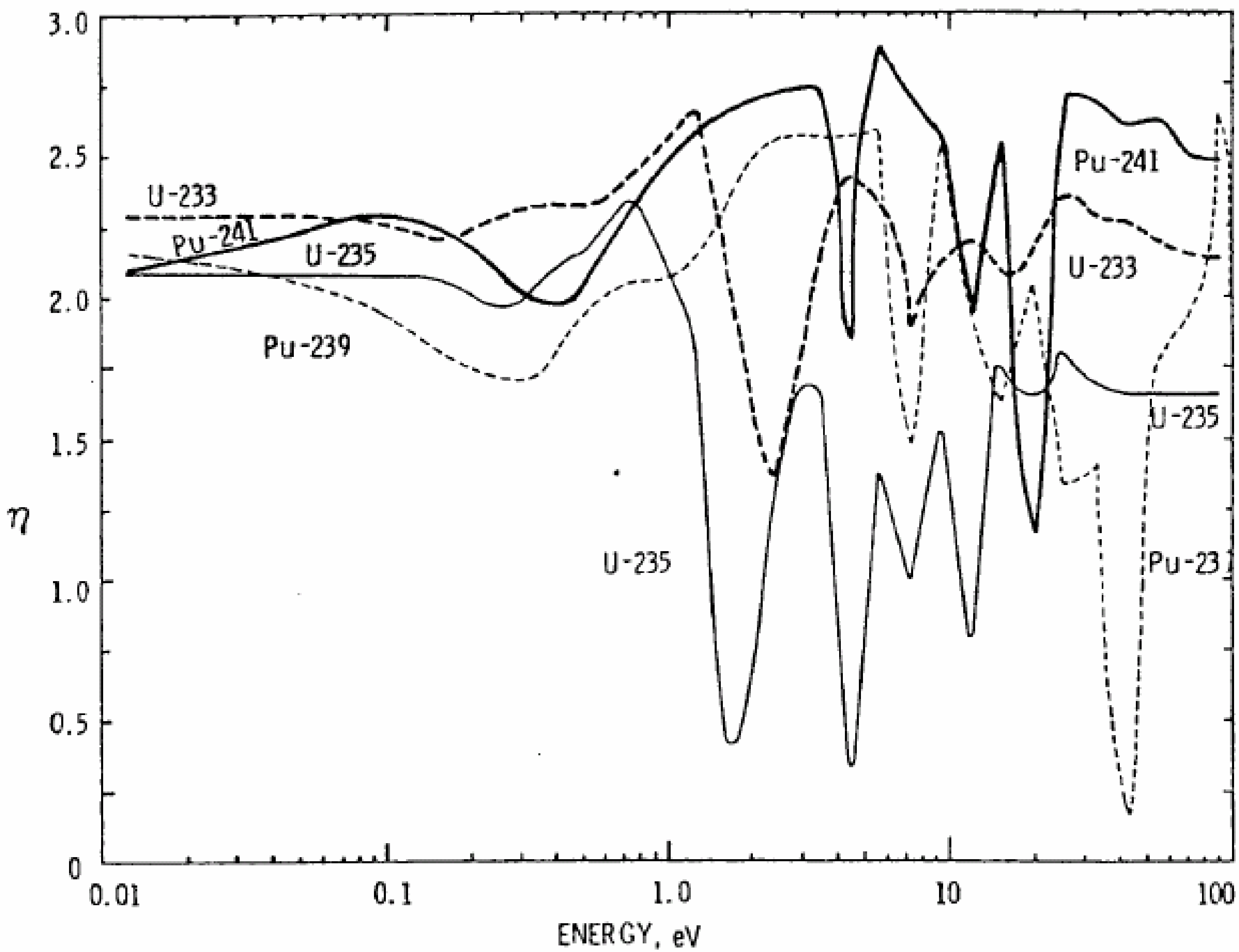
Fuel Burnup

- Depletion Equation

- Definition of burnup
  – thermal energy output per mass of fuel
  – MWD/MTHM

Transmutation

- Equation for production of any nuclide
- Conversion versus Breeding
  - Depending on core physics design of the reactor core
  - η (eta)
    - Number of neutrons produced/absorbed in fuel
- Conversion ratio
  - rate of creation of new fissile/destruction of existing fissile


3.0
2.5
2.0
1.5
1.0
0.5
0
η
0.01
0.1
1.0
10
100
ENERGY, eV
U-233
Pu-241
U-235
Pu-239
U-235
Pu-241
U-233
U-235
Pu-23

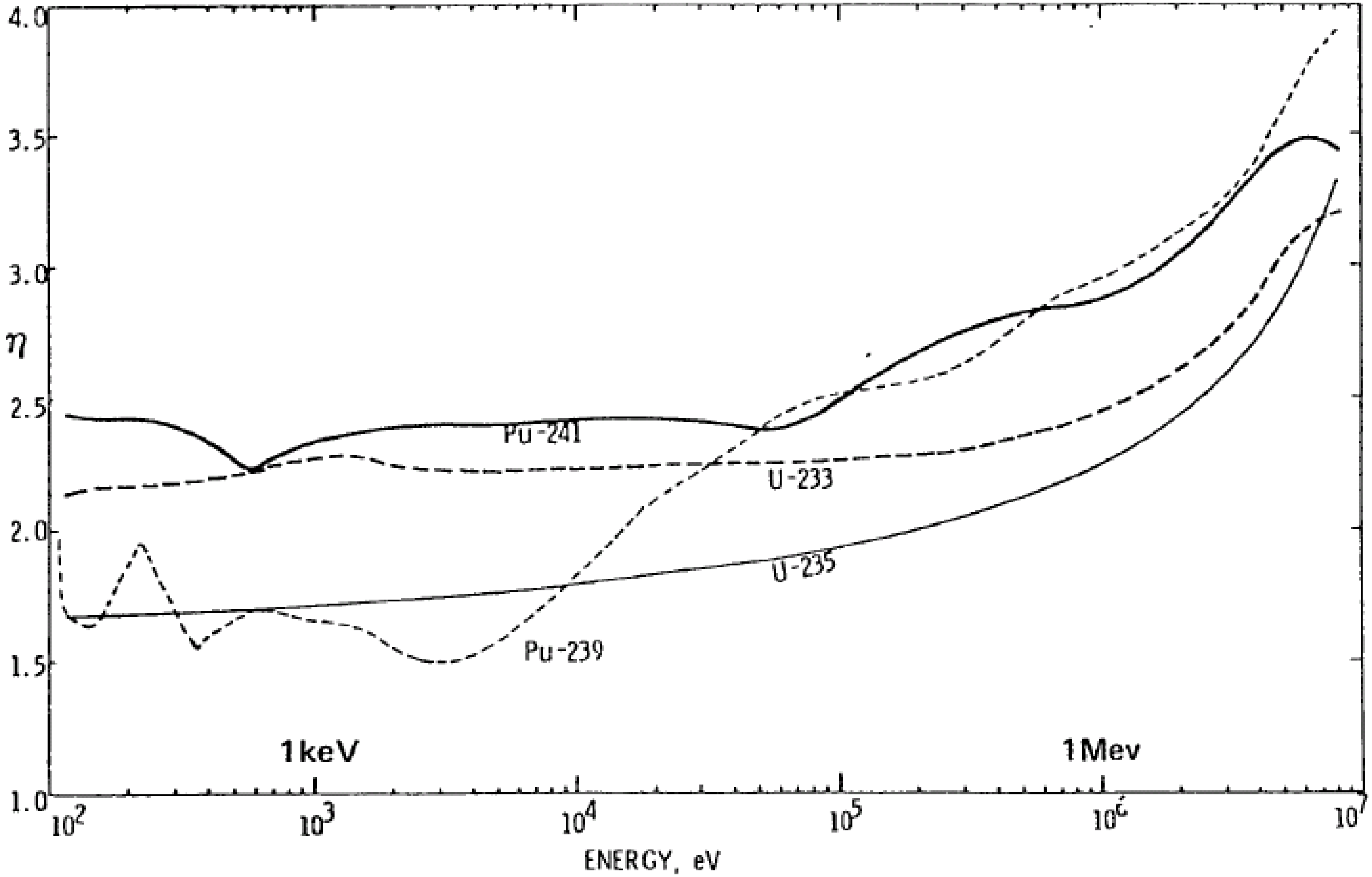


FIGURE 6-1

Values of eta [η] for fissile nuclides as a function of energy. [Courtesy of Electric Power Research Institute (Shapiro, 1977).]

Breeding Ratios for Reactor Systems

TABLE 6-1
Average Conversion or Breeding Ratios for Reference Reactor Systems

Reference reactor	Initial fuel†	Conversion cycle†	Conversion ratio	Breeding ratio
BWR	2–4 wt% ^{235}U	^{238}U–Pu	0.6	—
PWR	2–4 wt% ^{235}U	^{238}U–Pu	0.6	—
PTGR	1.8–2.1 wt% ^{235}U	^{238}U–Pu	$\geq$0.6	—
PHWR	Natural U	^{238}U–Pu	0.8	—
HTGR	$\approx$5 wt% ^{235}U	^{232}Th–^{233}U	0.8	—
LMFBR	10–20 wt% Pu	^{238}U–Pu	—	1.0–1.6

† All plutonium in power reactors is an isotopic mixture based on initial conversion of ^{238}U to ^{239}Pu and followed by transmutation to the "higher" isotopes.

Buildup of Plutonium with Burnup

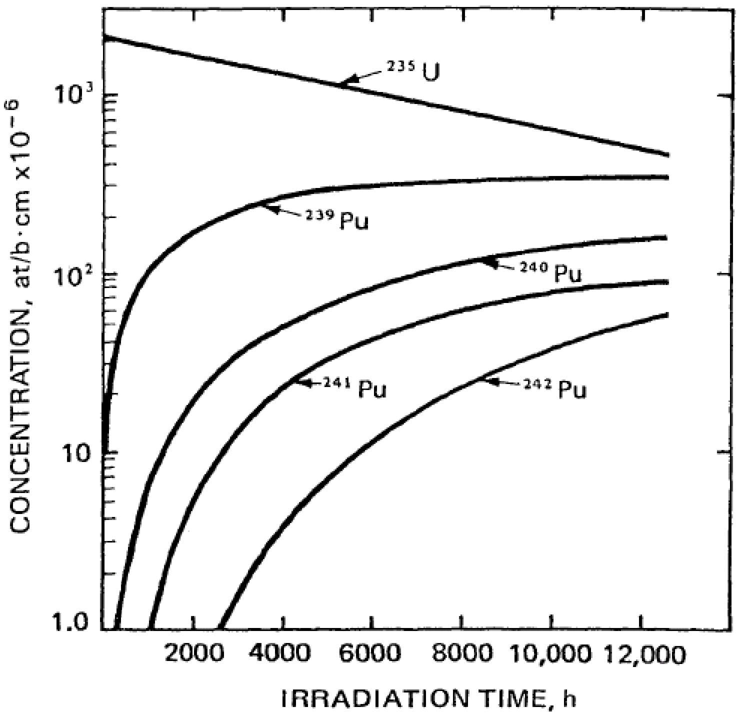


FIGURE 6-2
Buildup of plutonium isotopes with burnup for a representative LWR fuel composition.

http://atom.kaeri.re.kr/

Reactivity Penalty

TABLE 6-2
Reactivity Penalty from Selected Transmutation Products for Recycle of BWR Fuel†

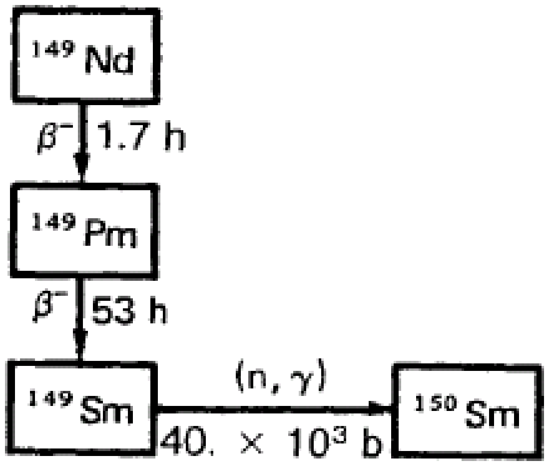
End of cycle number	Reactivity penalty at discharge, %Δk			
	^{236}U‡	^{237}Np§	^{242}Pu	^{243}Am§
1	0.62	0.13	0.65	0.36
2	0.90	0.59	1.53	0.57
3	1.12	0.73	2.04	0.89

†From A. Sesonske, *Nuclear Power Plant Design Analysis*, TID-26241, 1973.
‡The ^{236}U concentration is assumed not to decrease in the diffusion plant.
§Neptunium and americium are removed by reprocessing on each recycle.

Fission Products

- Fission Fragments → Fission Products
  - Rate of Creation - $\gamma \Sigma_f \Phi$
  - γ fission yield
- Fission Fragment Balance Equation

Samarium Buildup



(a)

FISSILE NUCLIDE	γ^{Nd}
^{233}U	0.0066
^{235}U	0.0113
^{239}Pu	0.0190

(b)

Samarium Buildup

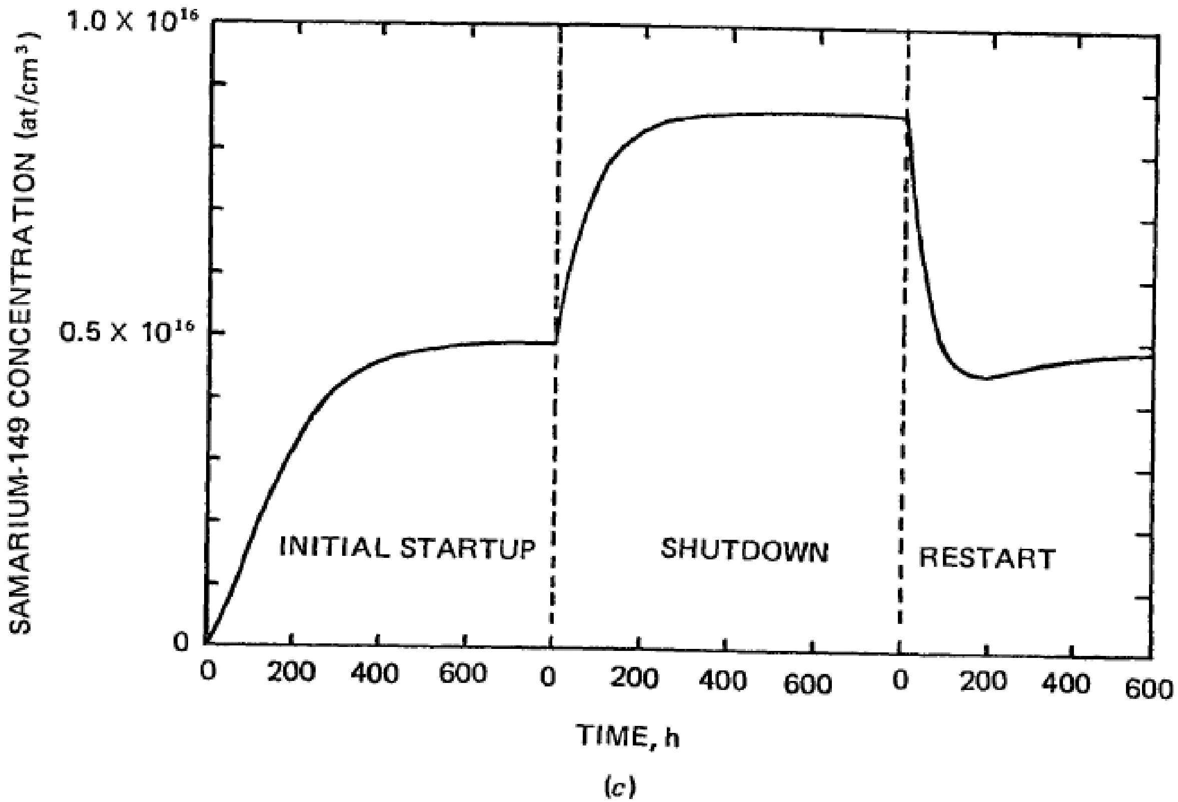
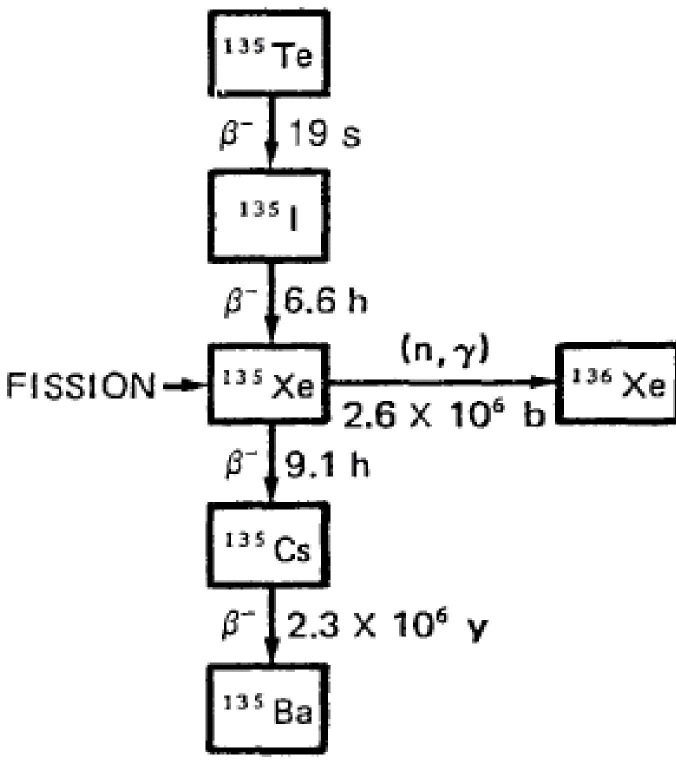


FIGURE 6-6
Behavior of ^{149}Sm in representative LWR fuel: (*a*) decay and reaction chain, (*b*) fission yields, (*c*) concentration vs. time.

Xenon Buildup

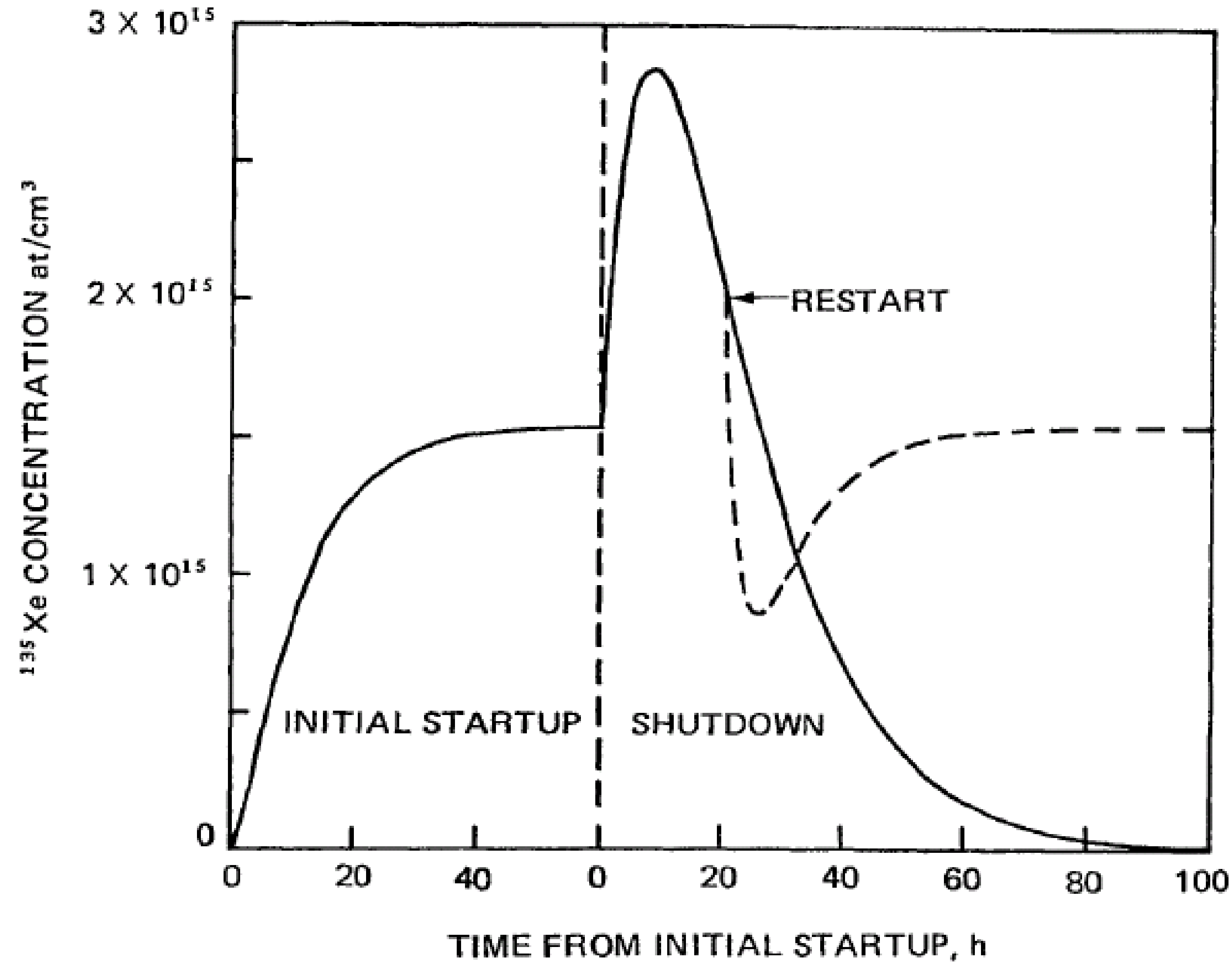


(*a*)

FISSILE NUCLIDE	$\gamma(^{135}Te)$	$\gamma(^{135}Xe)$
^{233}U	0.051	
^{235}U	0.061	0.003
^{239}Pu	0.055	

(*b*)

Massachusetts Institute of Technology
Department of Nuclear Science & Engineering



(*c*)

FIGURE 6-7

Behavior of ^{135}Xe in representative LWR fuel: (*a*) decay and reaction chain, (*b*) fission yields, (*c*) concentration vs. time.

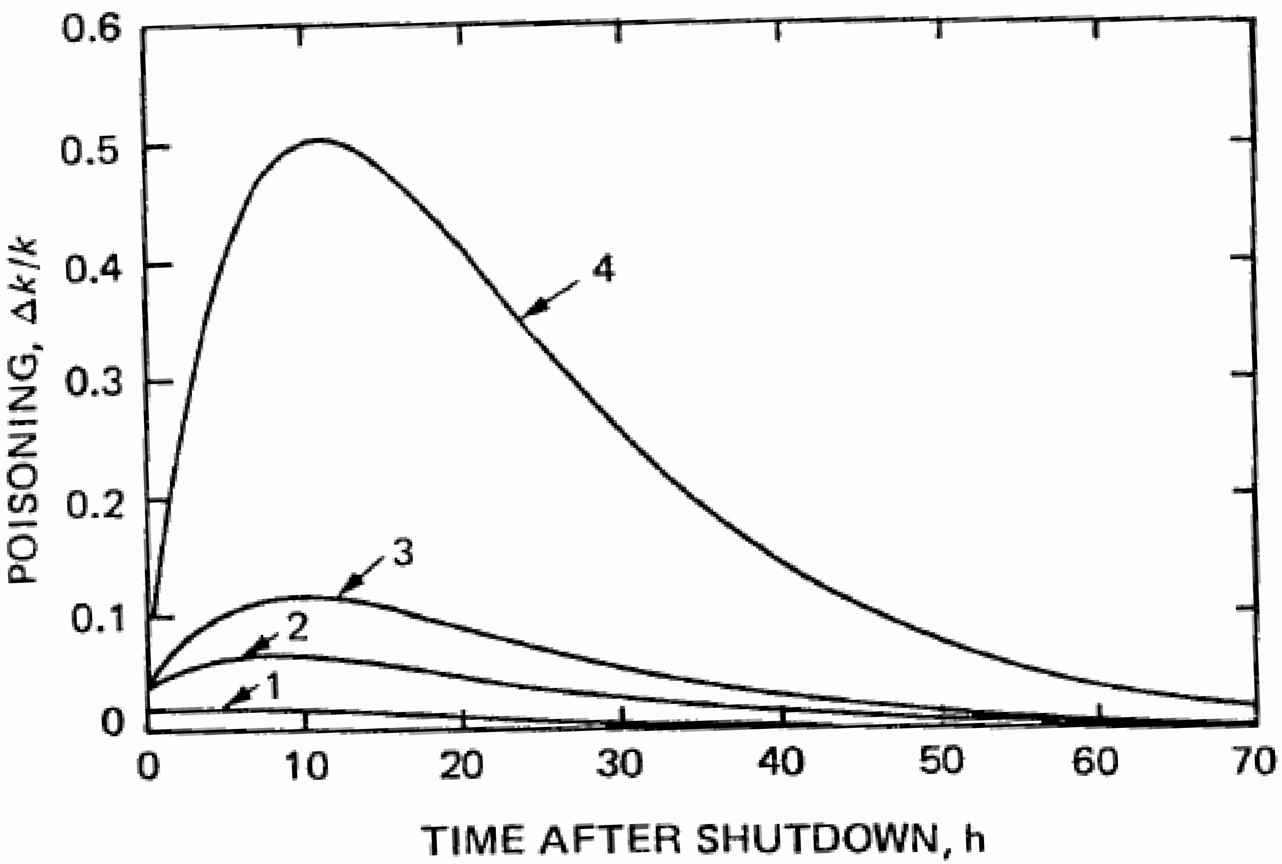


FIGURE 6-8

Poisoning of ^{135}Xe as a function of time after shutdown for a representative LWR fuel composition at various neutron flux levels. Curve 1: $\Phi = 1 \times 10^{13}$ n/cm²·s; Curve 2: $\Phi = 5 \times 10^{13}$ n/cm²·s; Curve 3: $\Phi = 1 \times 10^{14}$ n/cm²·s; Curve 4: $\Phi = 5 \times 10^{14}$ n/cm²·s.

Operational Impacts

- Xenon Oscillations
- Fuel Design for cycle length of core
- Fuel management strategies
- Power peaking limits
- Power distribution control

Reactor Physics Calculations

- Multi-Group Diffusion Equations
  - Model core – using fuel pin and assembly homogenization of materials and fuels with pins averaged horizontally but detailed axially
- Run Static calculation for core power and flux distribution
- Fluxes used to perform depletion calculations as noted for a “time step”
- New material calculations used to produce new power and flux distribution for next “time step” – 1 month
- Incorporate only significant isotopes – high absorption and/or fission cross sections ignoring short lived isotopes in decay chains. – use lumping procedure
- Need to consider early xenon and Samarium build up 50 hours/500 hours
- Track key isotopes for all fuel assemblies for refueling management

Homework Assignment

- Chapter 6
  - Problems: 6.2, 6, 7, 9, 11, 15

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