Operational Reactor Safety

22.091/22.903

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Lecture 3
Reactor Kinetics and Control

Topics to Be Covered

- Time Dependent Diffusion Equation
- Prompt Neutrons
- Delayed Neutrons
- Point Kinetics Equation
- Reactivity
- Inhour Equation
- Feedback - Fuel-Doppler, Moderator, Power
- Reactor Control

Key Concepts

- Time Dependent Diffusion Equation
  - Rate of change = rate of production – rate of absorption – rate of leakage
- Prompt neutron keff
- Reactivity – $\rho = (k - 1)/k$
- Mean neutron generation time $l^* = 10^{-7}\ sec$
- Reactor Period – $T = l^*/\rho$
  - *Time to increase power by factor of e*

Impact of Delayed Neutrons

- 99 % of Neutrons are Prompt – released at time of fission
- Fission Products also release neutrons with some delay based on half life - Precursors
- 20 Precursors grouped into 6 groups with half lives ranging from 0.25 sec to 1 minute
- Delayed neutron fraction
  - β_i = delayed neutrons from precursor group C_i /v

Delayed Neutrons

TABLE 5-2
Six-Precursor-Group Half-Lives and Delayed Neutron Fractions for Thermal Fission of $^{235}U^{\dagger}$

Group	Half-life $T_{1/2}$ (s)	Delayed fraction β_i
1	55.0	0.00021
2	23.0	0.00142
3	6.2	0.00127
4	2.3	0.00257
5	0.61	0.00075
6	0.23	0.00027
Total	–	0.0065

†Data from G. R. Keepin, T. F. Wimett, and R. K. Zeigler, "Delayed Neutrons from Fissionable Isotopes of Uranium, Plutonium, and Thorium," *Phys. Rev.*, vol. 107, 1957, pp. 1044–1049.

Neutron Balance

- Prompt source
- Delayed source
- Time Dependent Neutron Balance Equation

Key Kinetics Equations

- Point Kinetics Equations

- Inhour Equation

Average Delayed Neutron from Uranium and Plutonium

TABLE 5-3
Delayed Neutron Fractions and Effective Delayed Neutron Fractions for ^{233}U, ^{235}U, ^{239}Pu

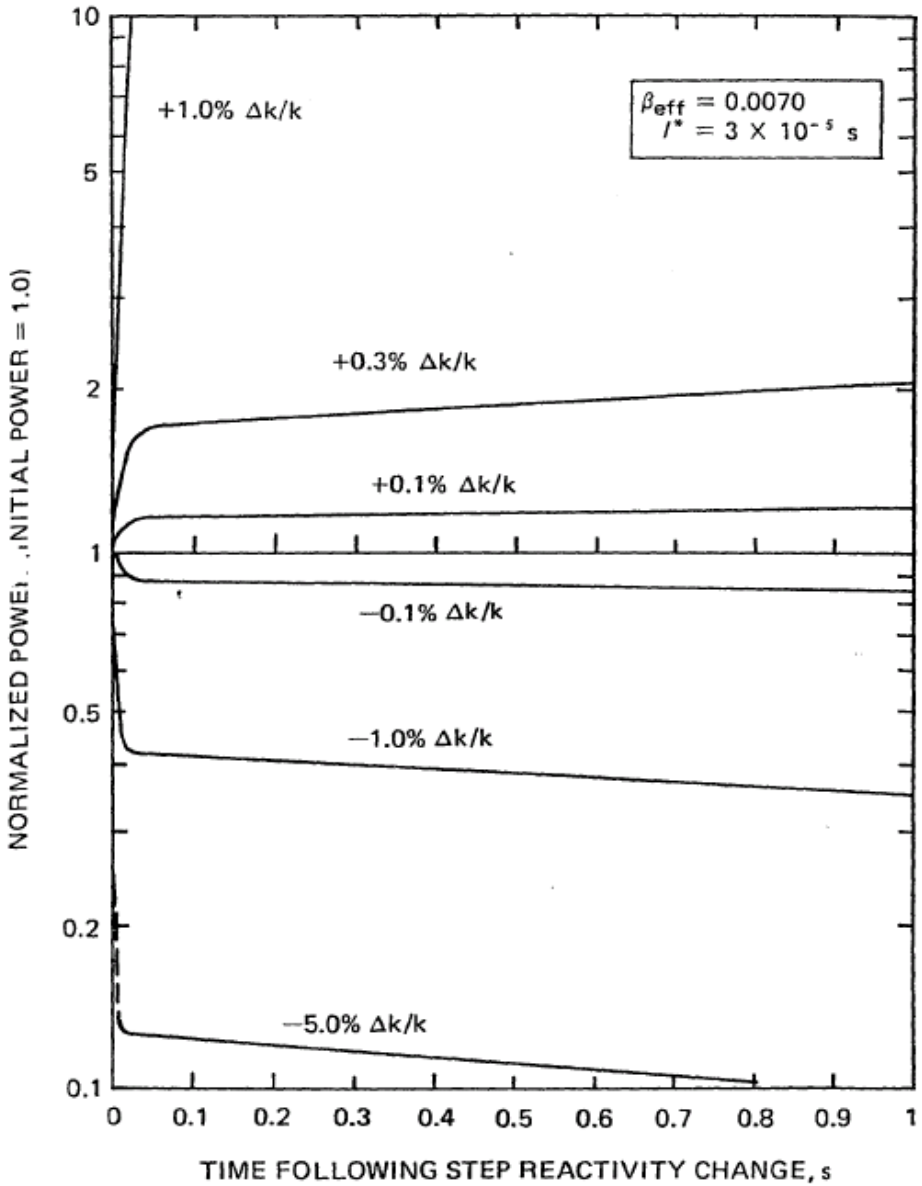
Nuclide	Delayed fraction β	Effective delayed fraction B_{eff} †
^{233}U	0.0026	0.003
^{235}U	0.0065	0.0070
^{239}Pu	0.0021	0.0023

†Typical for LWR systems.

Delayed neutrons are produced at about ½ the energy of prompt neutrons

Reactivity Insertions

- Reactor follows point kinetics equations
- Prompt jump – drop
- Asymptotic Period – considering delayed neutrons
- Prompt critical – transition to prompt from delayed control $\rho = \beta$
- Period of core used to start up reactor – 80 sec.



$$\$ = \rho/\beta$$

GURE 5-1
Time-dependent power behavior following various reactivity insertions representative of a reactor using slightly enriched uranium fuel.

Reactivity Feedbacks

- Fuel Temperature
  - Thermal expansion
  - Doppler
- Moderator/Coolant
- Fuel Motion – bowing

Reactivity Coefficients

- Fuel Temperature
- Moderator Temperature
- Moderator Density
- Void Coefficient
- Power Coefficient

Doppler Broadening

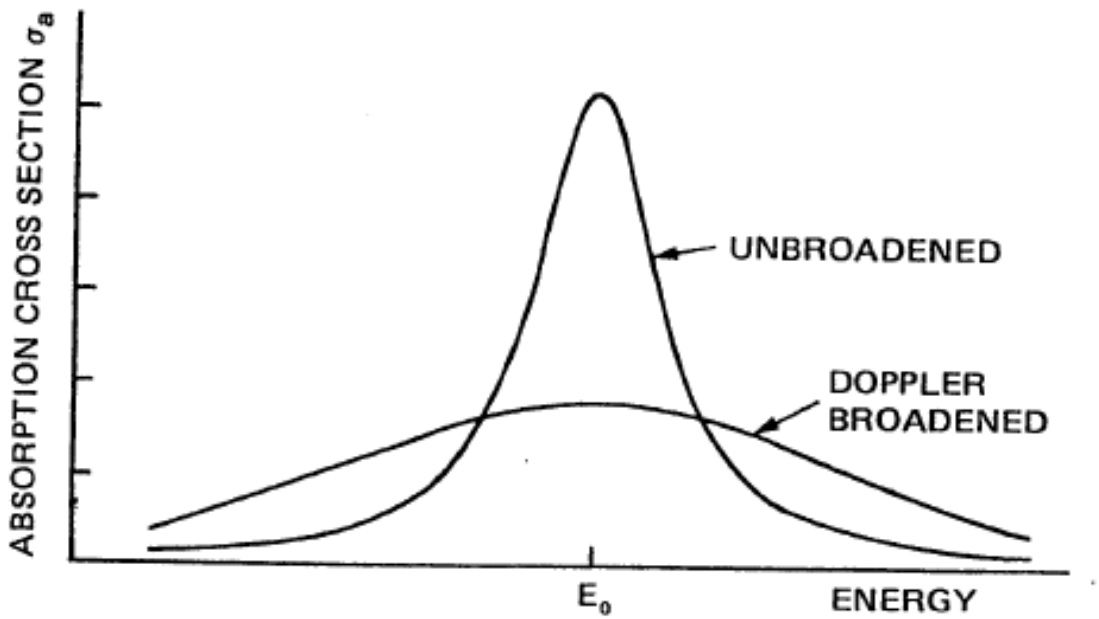


FIGURE 5-2
Effect of temperature on the effective shape of a resonance absorption cross section.

Reactivity Feedback

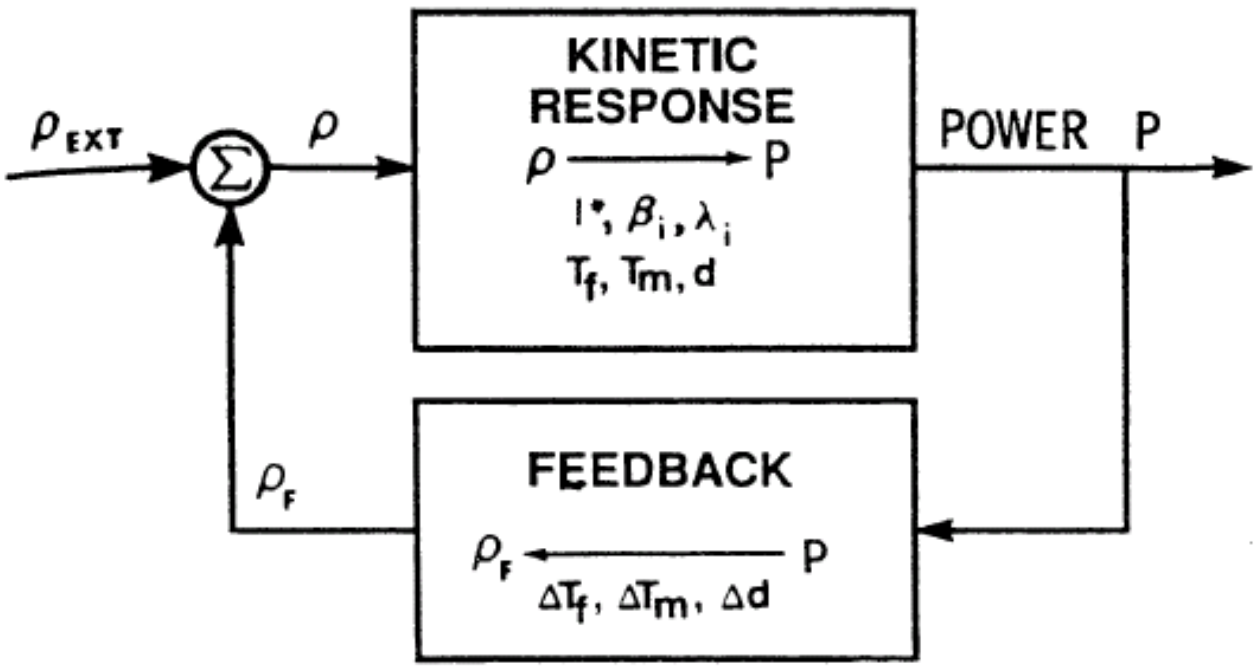


FIGURE 5-3
Reactivity feedback diagram.

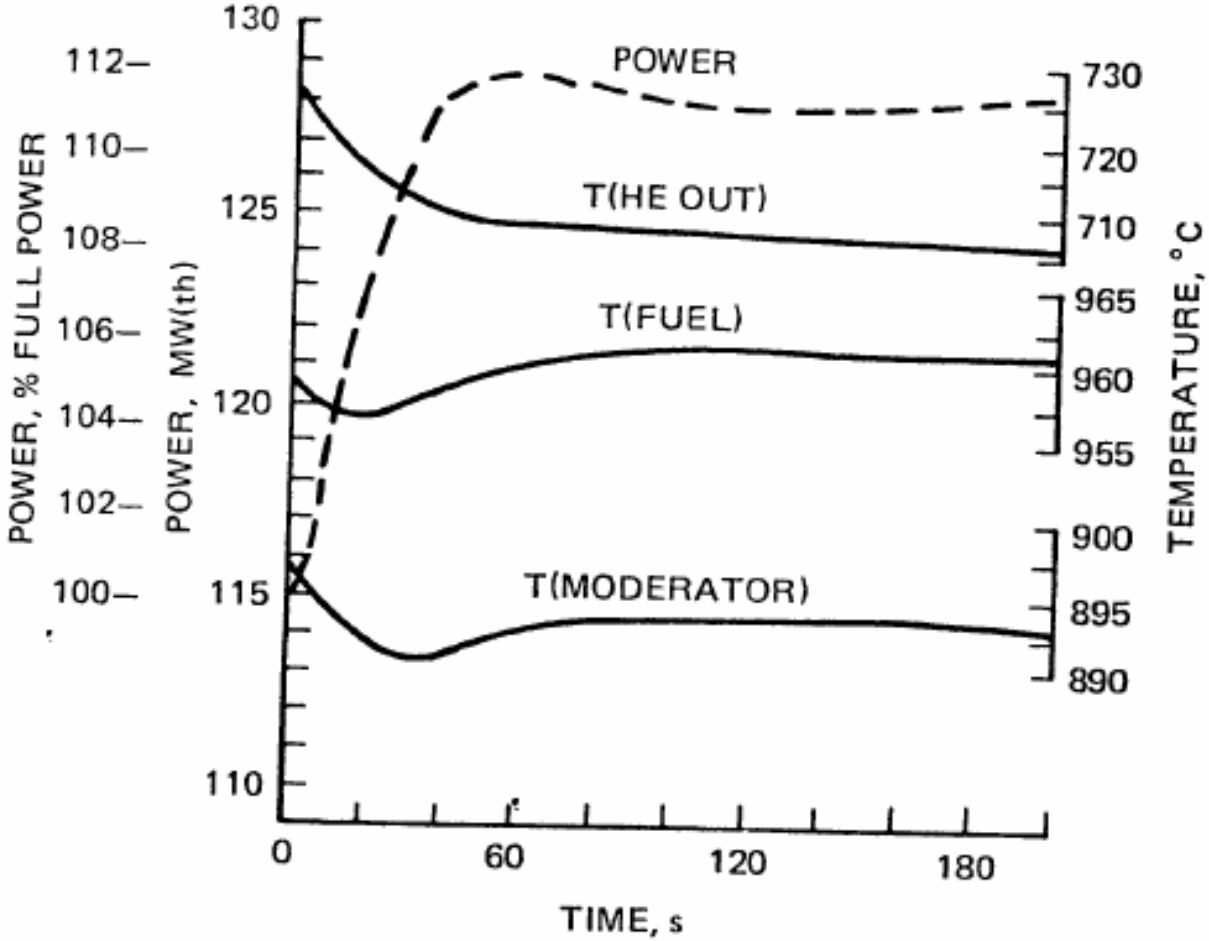


FIGURE 5-4

Response of the Peach Bottom HTGR to a 68°C decrease in helium inlet temperature (Adapted from *The Technology of Nuclear Reactor Safety*, T. J. Thompson and J. G. Beckerley (eds.), Vol. 1, by permission of The MIT Press, Cambridge, Massachusetts. Copyright © 1964 by the Massachusetts Institute of Technology.)

Reactor Control

- Inherent feedback mechanism
  - Fast – fuel
  - Slow – moderator
- Control Rods
  - Relatively fast but rod worth an issue
    - Rod ejection
    - Rapid withdrawal
- Soluable Boron – effect on Moderator Temp. Coefficient

Homework Assignment

- Knief Chapter 5
  - Problems: 1,4,6,9
- Read Chapter 6 for next class

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