Introduction to Reactivity and Reactor Control

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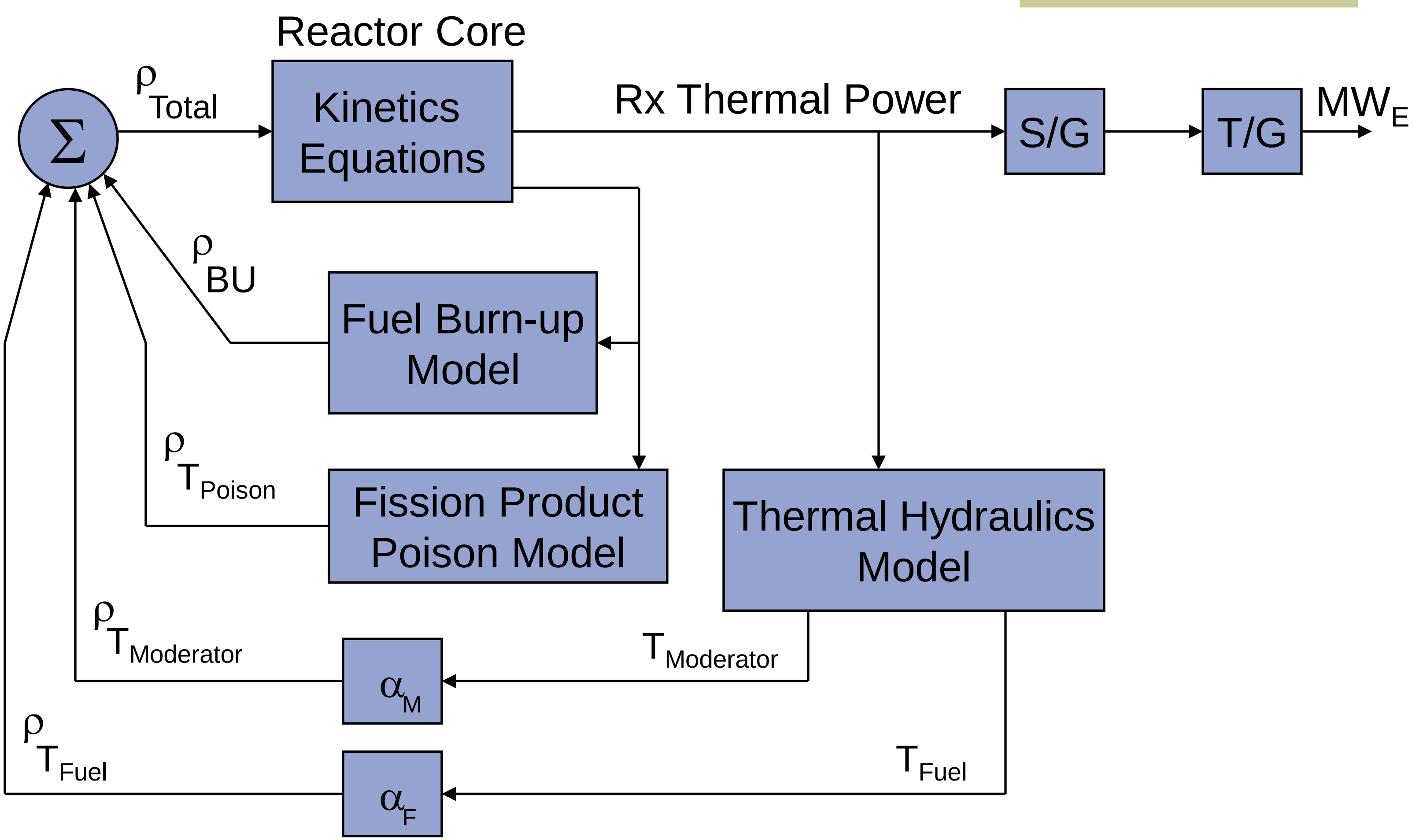
Learning Objectives

- Define k-effective (k_{eff}) and reactivity, and describe their importance in reactor dynamic behavior.
- Describe the units used to represent reactivity.
- Write the time dependent neutron balance and describe what can happen to neutrons in a reactor.
- Describe the important role of delayed neutrons.
- Describe the inherent reactivity effects in a nuclear reactor.
- Describe the natural phenomena and designed systems that can change reactivity.

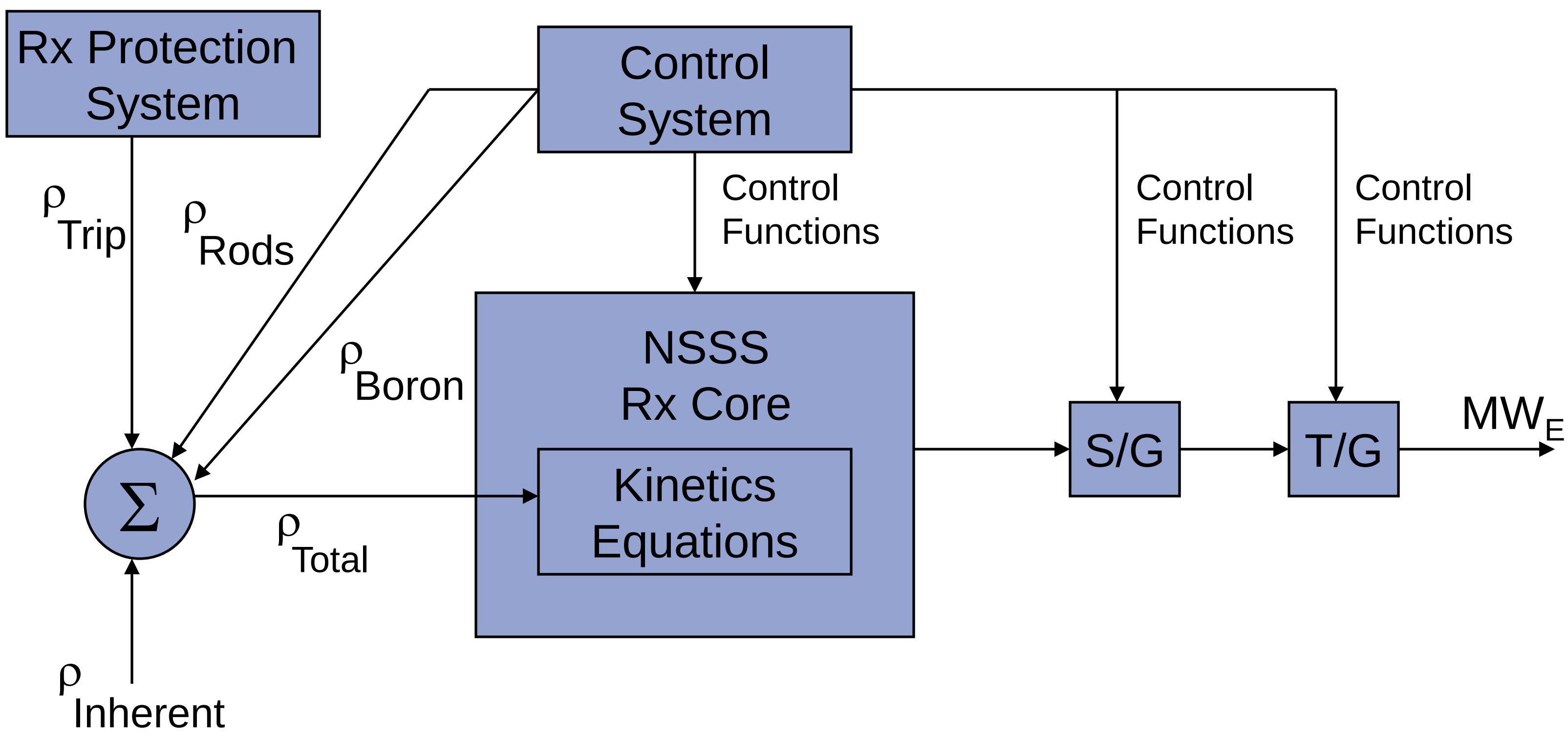
Learning Objectives

- Describe the signals from process measurements are used to control the reactor.
- Identify and discuss steady state, heat balance relationships in a pressurized water reactor.
- Discuss and critique alternative philosophies for reactor control.
- Understand and illustrate the effects of fission product buildup on reactivity and core kinetics.
- Differentiate among critical, supercritical, and subcritical conditions in a reactor.

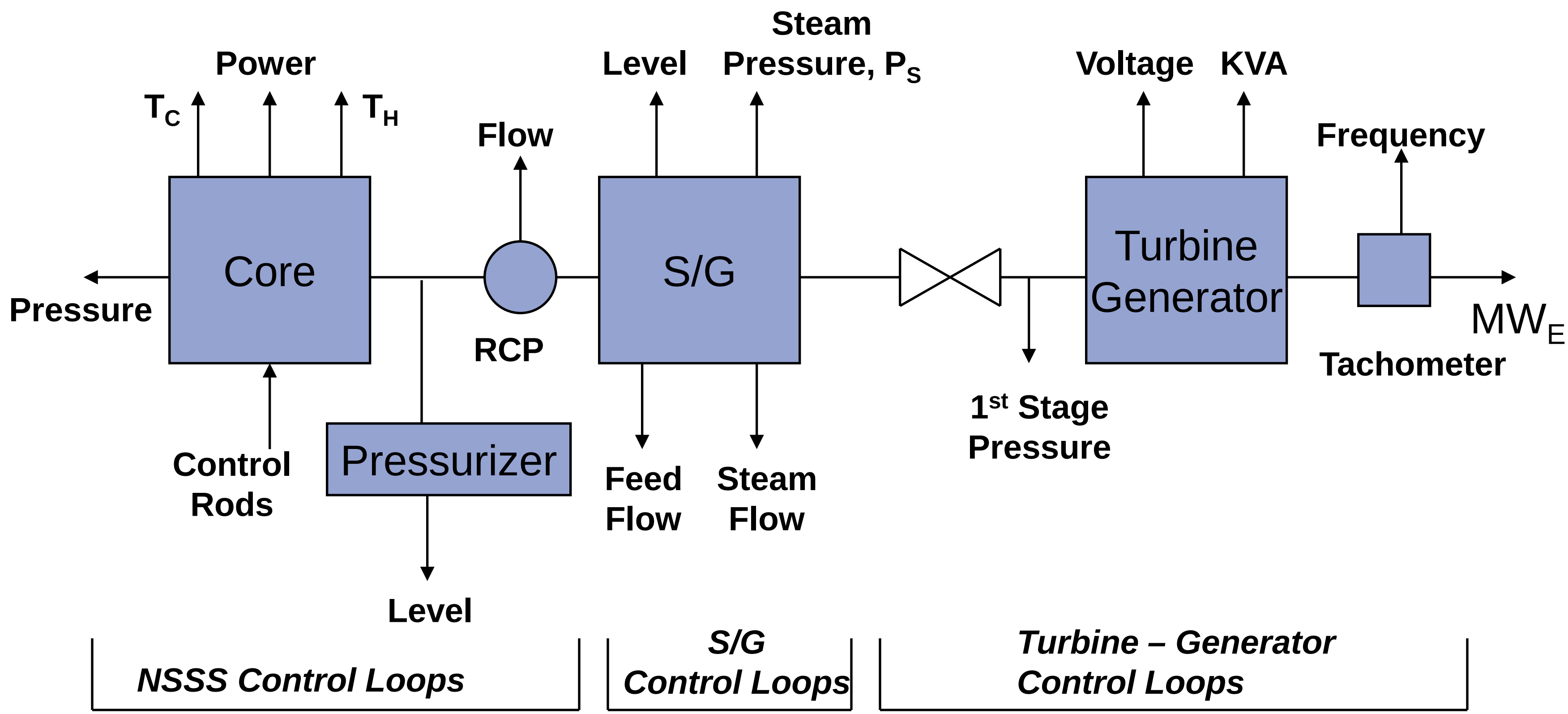
Inherent Reactivity Effects



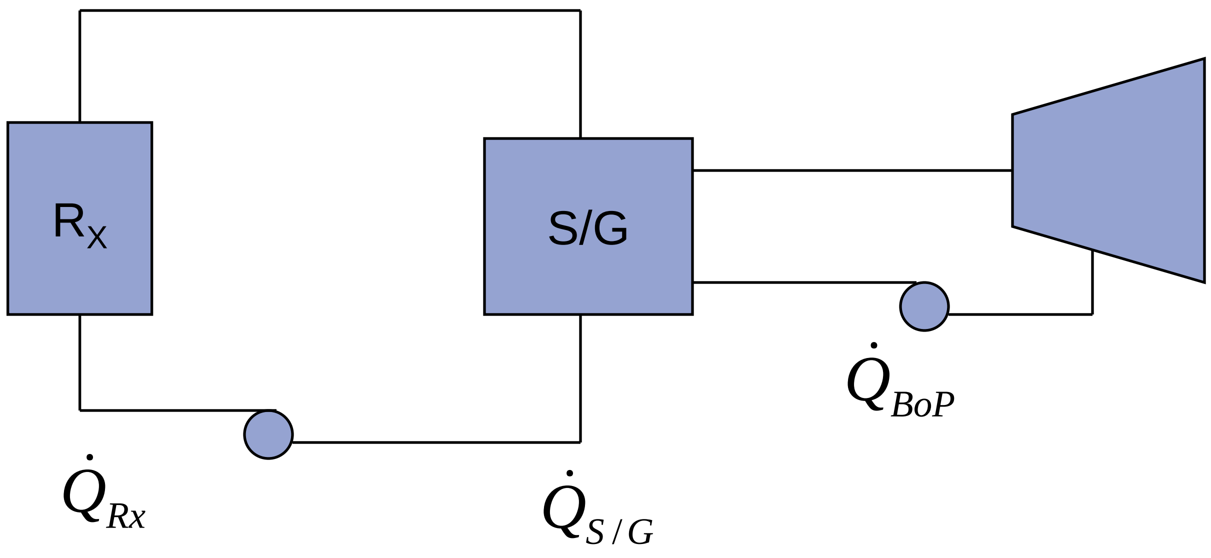
External Reactivity Effects by Protection and Control Systems



Signals for Protection and Control



Concepts for Control
Steady State Operation



In steady state, all heat terms are equal given no losses.

Concepts for Control
Important Relationships

Two balance equations must be satisfied for the reactor to be steady-state:

$$1.\ \rho_{Total} = 0$$

$$2.\ \dot{Q}_{RX} = \dot{Q}_{S/G} = \dot{Q}_{BoP}$$

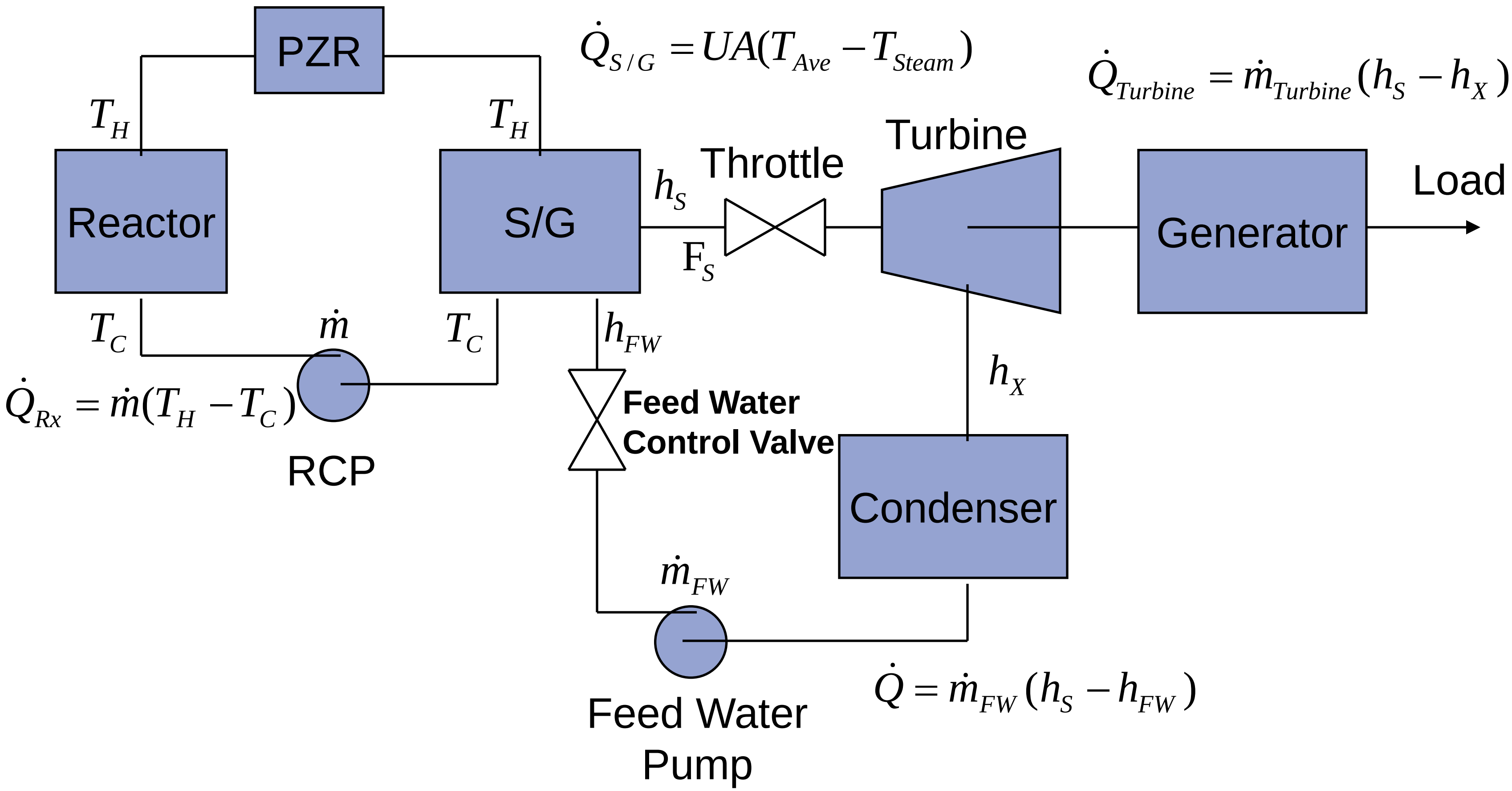
The following three equations can be used to calculate each of the above Q terms:

$$\dot{Q}_{Rx} = \dot{m}_{RCP} C_p (T_H - T_C)$$

$$\dot{Q}_{S/G} = UA(T_{ave} - T_{Steam})$$

$$\dot{Q}_{BoP} = \dot{m}_{Feed\,Water} (h_{steam} - h_{Feed\,Water})$$

Concepts for Control
One-line Drawing of a PWR



Response Curves

Constant Tav Program

Advantages:

•Least amount of external control

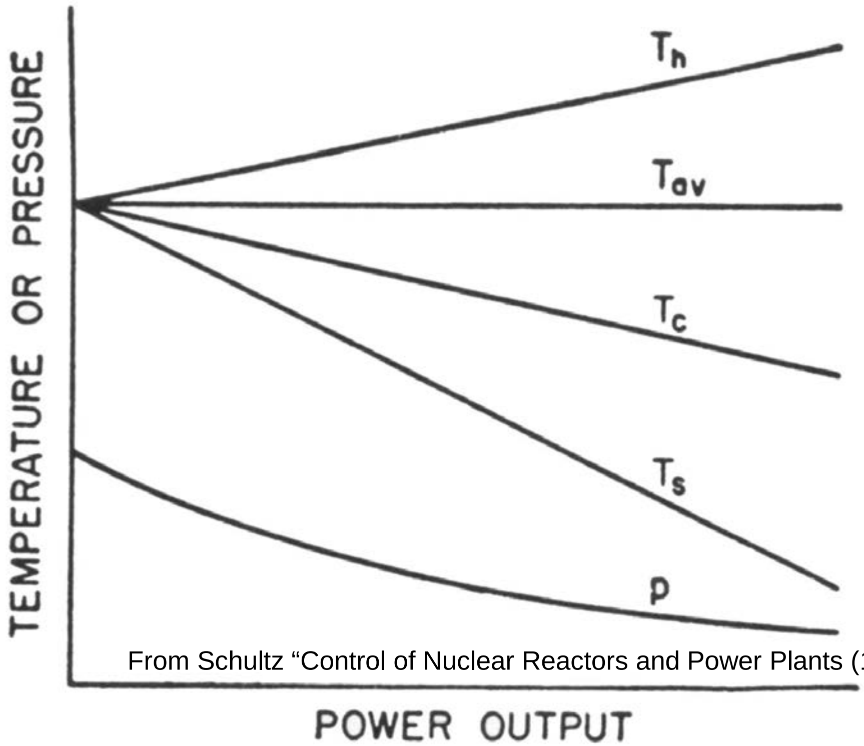
•Preferred by reactor

•Small pressurizer (minimum expansion of coolant volume as power changes)

Disadvantages

•Drop off of steam temperature and pressure

•Poor turbine efficiency



From Schultz "Control of Nuclear Reactors and Power Plants (1961)

FIG. 8-4. Variations in temperatures and pressure as a function of power output for constant-average-temperature program with fixed coolant flow.

Response Curves

Constant Th Program

Advantages:

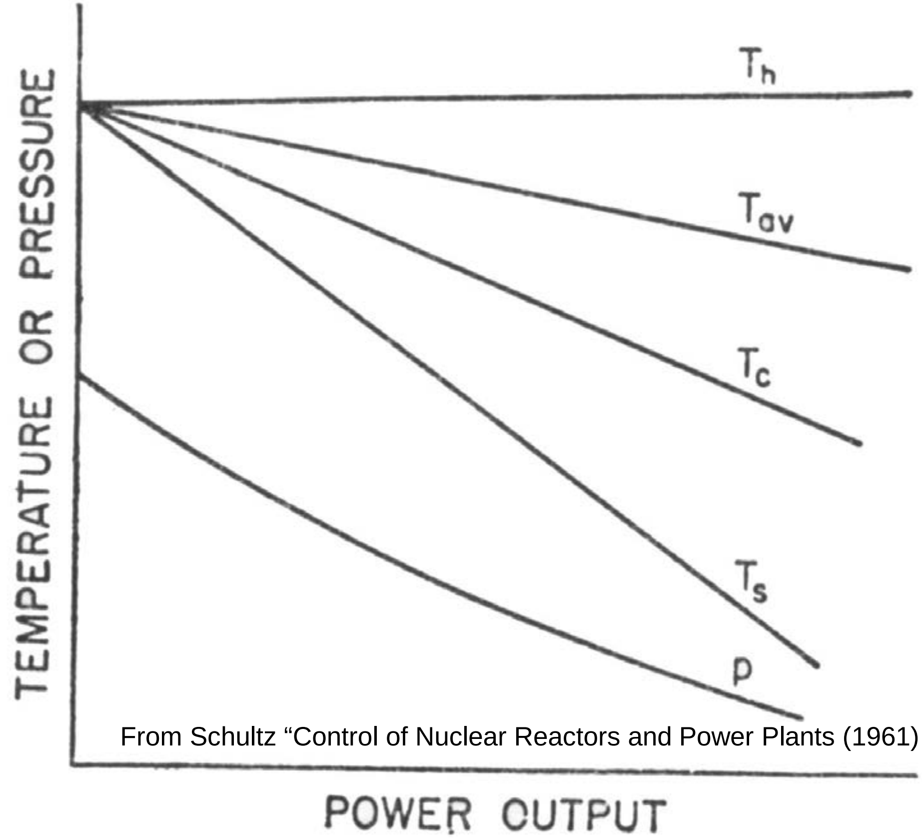
•Least stressful to materials

Disadvantages

•Huge drop off of steam temperature and pressure

•Poorest turbine efficiency

•Requires external reactivity control



From Schultz "Control of Nuclear Reactors and Power Plants (1961)

FIG. 8-6. Variations in temperatures and pressure as a function of power output for constant-outlet-temperature program.

Response Curves

<u>Constant Tsteam Program</u>

<u>Advantages</u>:

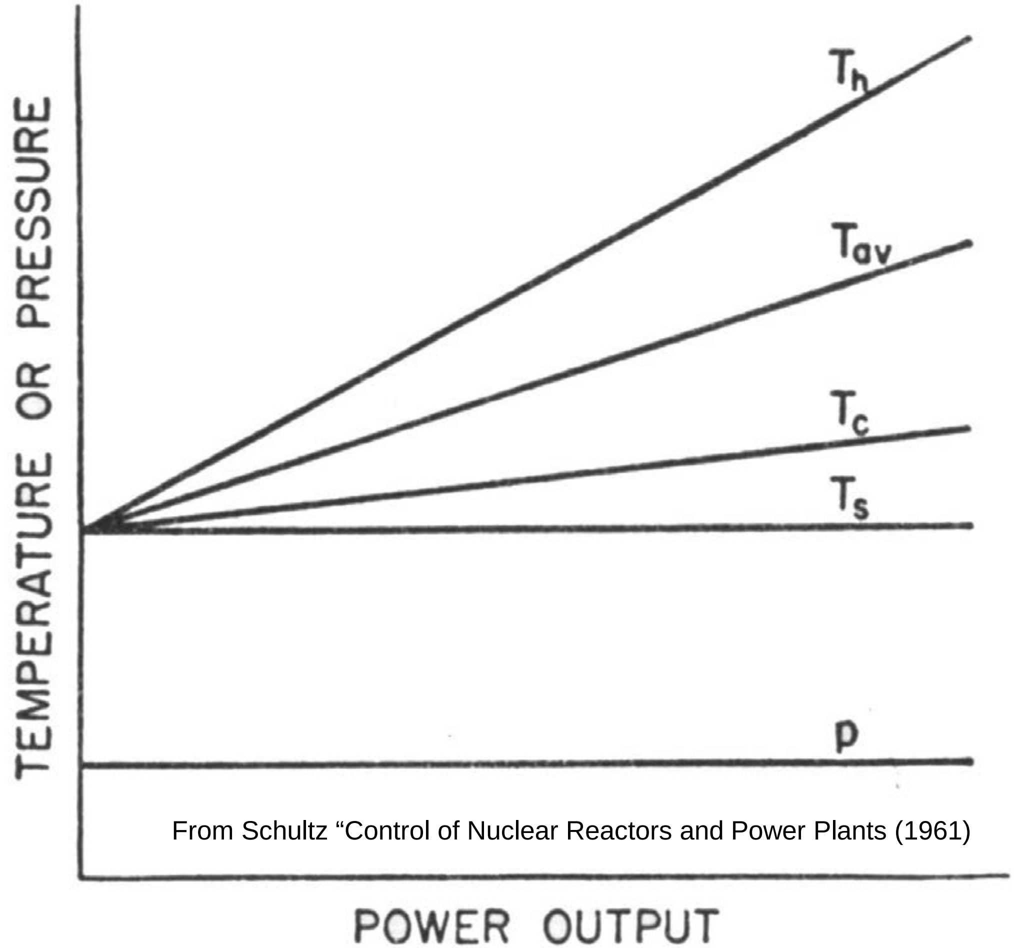
•Best turbine efficiency

•Preferred by turbine

<u>Disadvantages</u>

•Need large pressurizer volume to accommodate coolant expansion

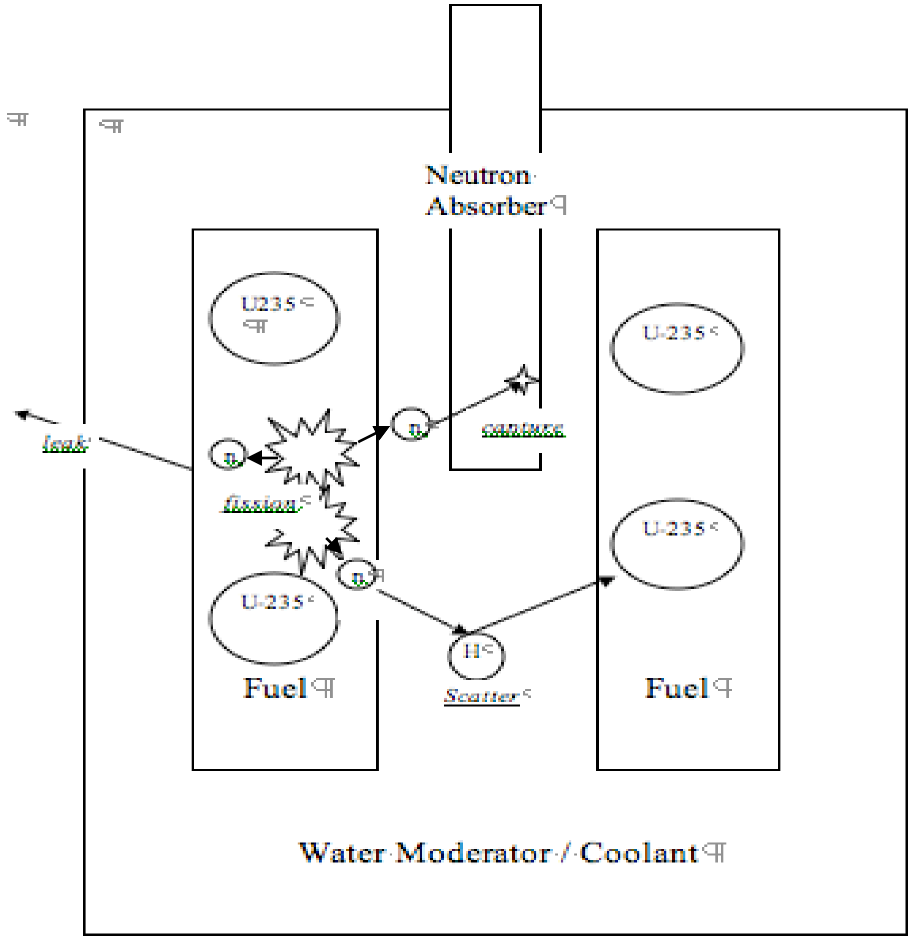
•Requires external reactivity control



From Schultz "Control of Nuclear Reactors and Power Plants (1961)

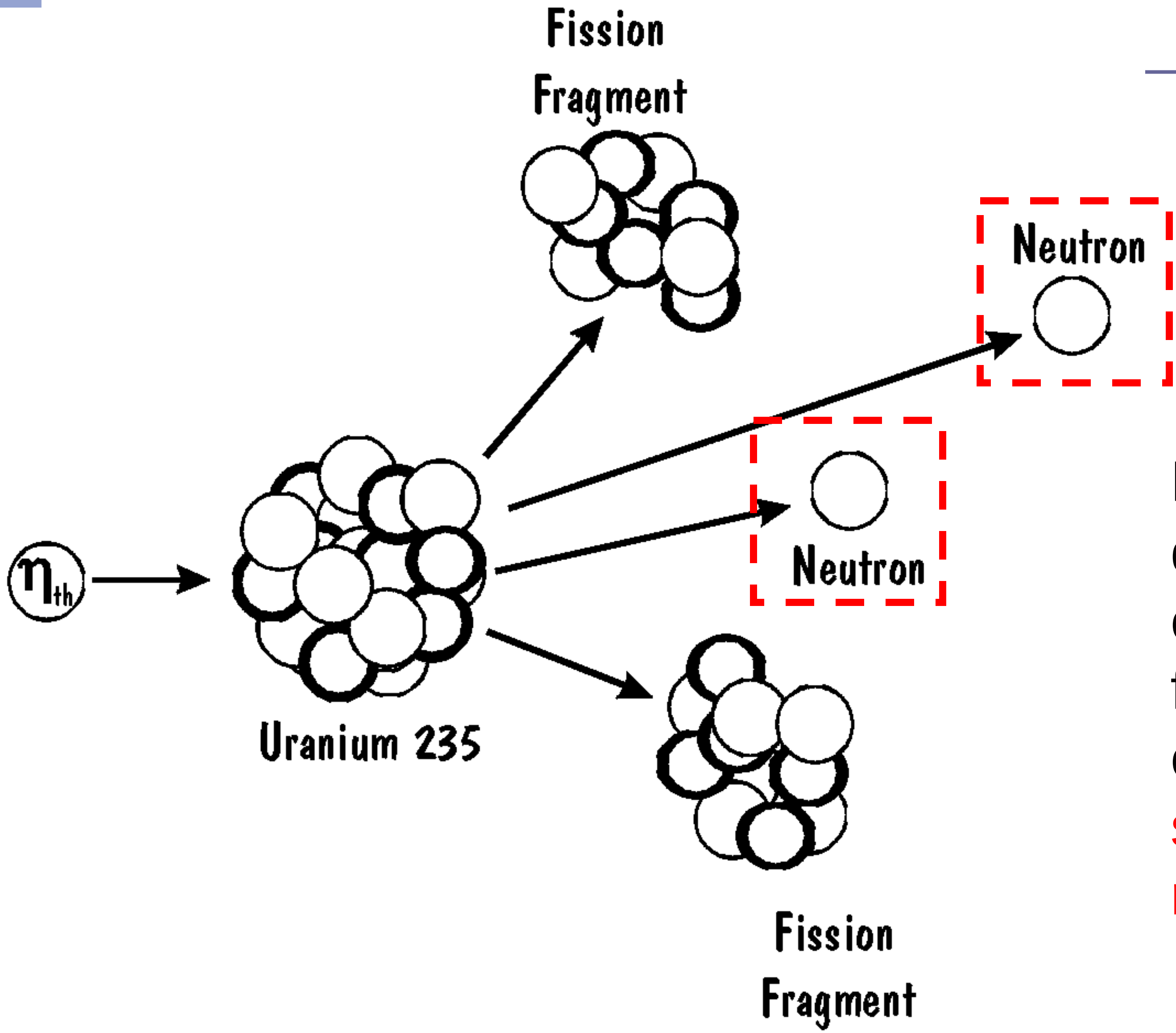
Reactor Physics 101

What Can Happen to Neutrons?



1. Fission
   a. Energy Release
      i. prompt
      ii. delayed
   b. Fission Products
   c. More Neutrons
      i. prompt neutrons
      ii. delayed neutrons
2. Capture
3. Scatter
4. Leak

Nuclear Fission



Neutrons emitted during fission can cause additional fission events, creating a self-sustaining chain reaction.

Neutron Balance

$$\begin{bmatrix} \text{Rate of Increase} \\ \text{in Number} \\ \text{of Neutrons} \end{bmatrix} = \begin{bmatrix} \text{Rate of} \\ \text{Production} \\ \text{of Neutrons} \end{bmatrix} - \begin{bmatrix} \text{Rate of} \\ \text{Absorption} \\ \text{of Neutrons} \end{bmatrix} - \begin{bmatrix} \text{Rate of} \\ \text{Leakage} \\ \text{of Neutrons} \end{bmatrix}$$

Accumulation = Production − Absorption − Leakage

If Accumulation:

= 0	Critical	Steady State	Static
> 0	Supercritical	Increasing	Kinetic/ Dynamic
< 0	Subcritical	Decreasing	Kinetic/ Dynamic

Effective multiplication and reactivity

$$k_{eff} = \frac{\text{neutron production rate}}{\text{neutron destruction rate}}$$

$$Let\ P = \text{production rate} = \nu F \text{ where } F = \text{fission rate}$$

$$\text{and } \nu = \text{number of neutrons per fission}$$

$$Let\ A = \text{absorption rate (loss)}$$

$$Let\ L = \text{leak rate (loss)}$$

$$\text{Then } k_{eff} = \frac{P}{A + L}$$

Effective multiplication and reactivity

- STATES OF CRITICALITY

  $k_{eff} = 1$ Critical

  $k_{eff} > 1$ Supercritical

  $k_{eff} < 1$ Subcritical

- DEFINITION OF REACTIVITY, ρ

$$\rho = \frac{k_{eff} - 1}{k_{eff}} = \frac{\Delta k}{k} = \frac{\frac{P}{A+L} - 1}{\frac{P}{A+L}} = \frac{P - A - L}{P} = \frac{net\ neutron\ production}{neutron\ production}$$

$\rho = 0$ Critical

$\rho > 0$ Supercritical

$\rho < 0$ Subcritical

Criticality

- States of criticality

  $k_{\mathrm{eff}} = 1$ Critical (ρ=0)

  $k_{\mathrm{eff}} > 1$ Supercritical (ρ>0)

  $k_{\mathrm{eff}} < 1$ Subcritical (ρ<0)

- No reactor can be constantly critical
  - Fuel depletion
  - Fission product buildup
  - Temperature changes

Note: k *and* k_{eff} *are used interchangeably*

Criticality Control

- States of criticality

  $k_{\text{eff}} = 1$ Critical ($\rho=0$)

  $k_{\text{eff}} > 1$ Supercritical ($\rho>0$)

  $k_{\text{eff}} < 1$ Subcritical ($\rho<0$)

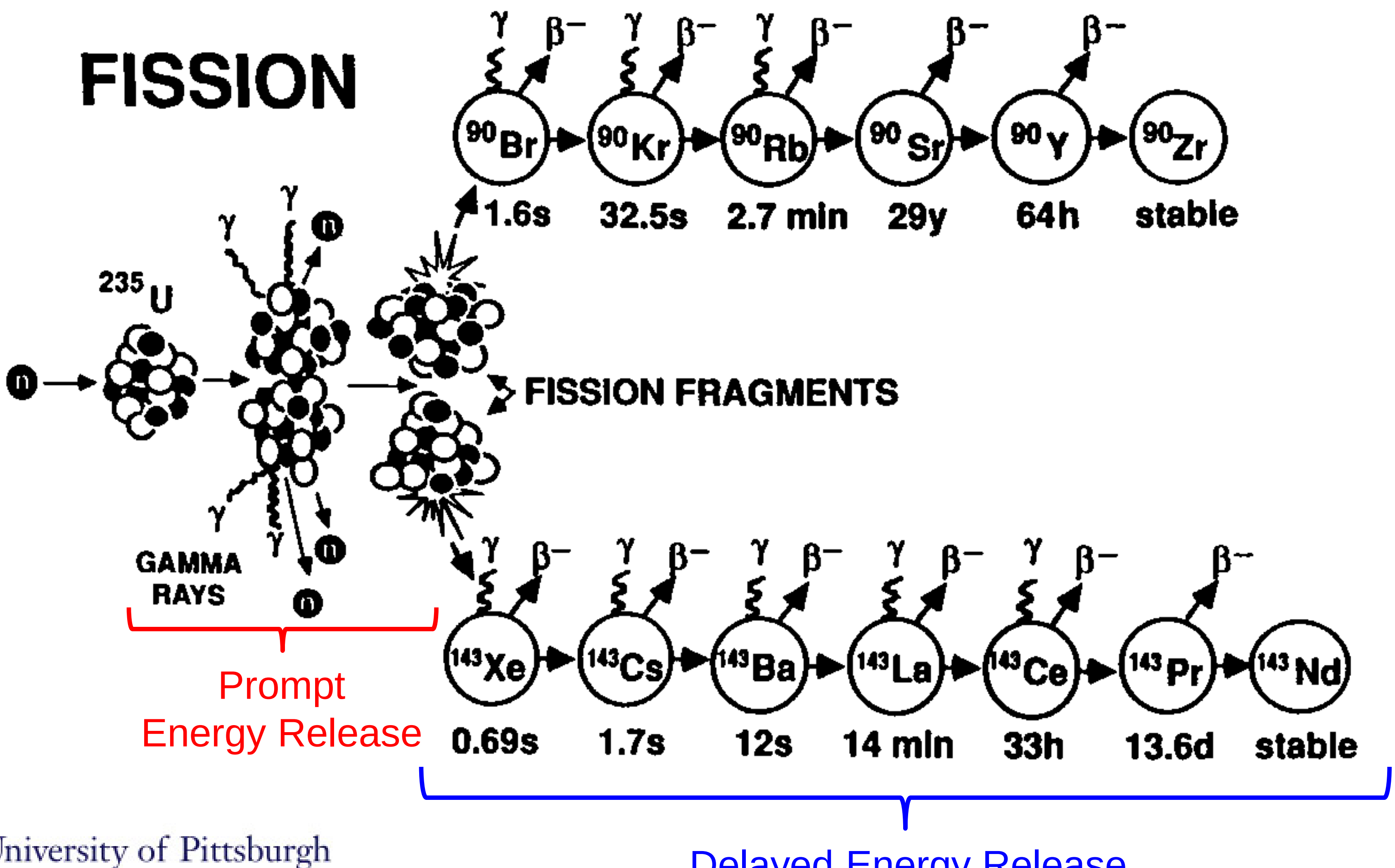
- In order to keep an operating nuclear reactor critical we will need to “adjust” terms in the neutron balance
- Neutron balance controls
  - Production
  - Absorption
  - Leakage

Reactivity Units

Units for Reactivity:

- mk (1 mk = 0.001)
- pcm (1 pcm = 0.00001)
- $\Delta\rho$ (given as number without units)
- $\Delta k/k$ (given as number without units)
- $\delta k/k$ (same as $\Delta k/k$)
- $\%\Delta k/k$ ($\Delta k/k$ x 100)
- $\$ = \Delta\rho/\beta$
- ¢ = 0.01 $

Energy Released During Fission



Neutron Balance with Delayed Neutrons

Neutron Balance

$$\begin{bmatrix}\text{Rate of Increase}\\ \text{in Number}\\ \text{of Neutrons}\end{bmatrix} = \begin{bmatrix}\text{Rate of}\\ \text{Production of}\\ \text{Prompt Neutrons}\end{bmatrix} + \begin{bmatrix}\text{Rate of Production}\\ \text{of Delayed Neutrons}\\ \text{from Precursor Decay}\end{bmatrix} - \begin{bmatrix}\text{Rate of}\\ \text{Absorption}\\ \text{of Neutrons}\end{bmatrix} - \begin{bmatrix}\text{Rate of}\\ \text{Leakage}\\ \text{of Neutrons}\end{bmatrix}$$

$$\frac{dn(t)}{dt} = (1-\beta)P(t) + \sum_{i=1}^{I}\lambda_i C_i(t) - A(t) - L(t)$$

Precursor Balance

$$\begin{bmatrix}\text{Rate of Increase}\\ \text{in Number}\\ \text{of Precursors}\end{bmatrix}_i = \begin{bmatrix}\text{Rate of}\\ \text{Production}\\ \text{of Precursors}\end{bmatrix}_i - \begin{bmatrix}\text{Rate of}\\ \text{Radioactive Decay}\\ \text{of Precursors}\end{bmatrix}_i \quad for\ i = 1,\ldots,I$$

$$\frac{dC_i(t)}{dt} = \beta P(t) - \lambda_i C_i(t) \quad for\ i = 1,\ldots,I$$

where β = fraction of neutrons delayed

Criticality Control (Reactor)

- Nuclear Reactor
  - **Production**
    - Determined by the total fissile content of the core.
    - Initial fuel loading.
  - Absorption
  - Leakage

Criticality Control (Reactor)

- Nuclear Reactor
  - Production
  - **Absorption**
    - Cladding, Structure, Coolant
    - Control Rods
    - Soluble Neutron Absorbers
    - Burnable Neutron Absorbers
    - Fission-Product Absorbtion
  - Leakage

Criticality Control (Reactor)

- Nuclear Reactor
  - Production
  - **Absorption**
    - Modern reactor designs
      - Moveable control rods (CR) to change power level and maintain steady state operation.
      - Movable safety rods (SR) to quickly shut down reactor and ensure $k_{\text{eff}} < 1$.
      - Soluble boron in reactor coolant (PWR only) to “shim” k_{eff}.
      - Fixed burnable absorbers (boron or gadolinium) that deplete during operation.
  - Leakage

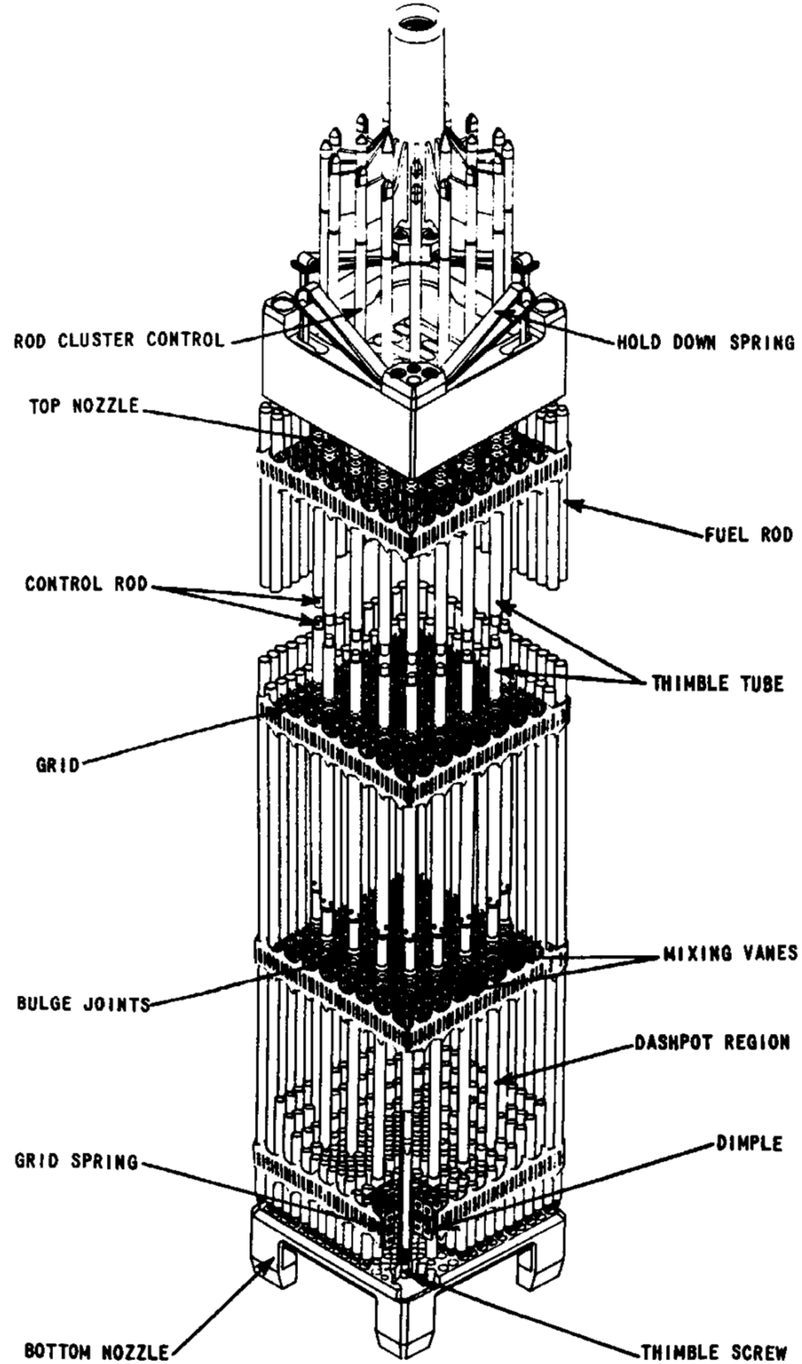
Criticality Control (Reactor)

- Nuclear Reactor
  - Production
  - Absorption
  - **Leakage**
    - Primarily determined by reactor design
    - Modern reactor designs:
      - Use a cylindrical core shape to reduce surface-to-volume ratio while still allowing easy access to fuel
      - Include a material (usually water) surrounding the core to reflect escaping neutron back into the active fuel region of the core

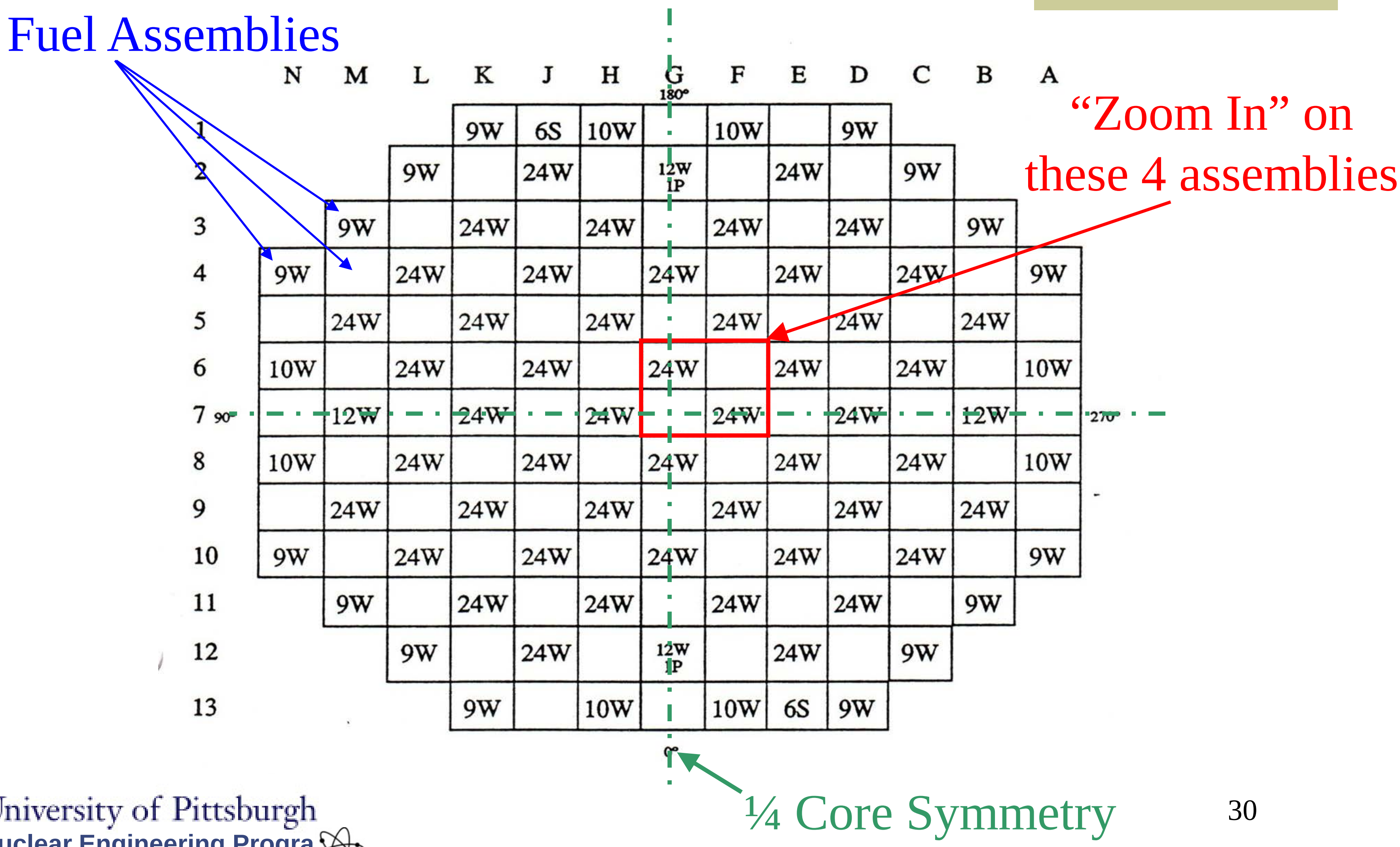
Criticality Control (Reactor)

- Reactor Criticality Requirements
  - Operation Modes
    - Power Reactors (Startup / Steady-State / Shutdown)
    - All reactors have emergency shutdown (SCRAM or TRIP) capability
  - Routine adjustments to reactor criticality are required
    - Account for power fluctuations and feedback effects
      - Fuel depletion, density changes of moderator
    - Small frequent adjustments: control rods (in PWR)
    - Larger, planned, adjustments: soluble boron (in PWR)
    - BWR reactors use control rods and coolant flow feedback to adjust criticality.

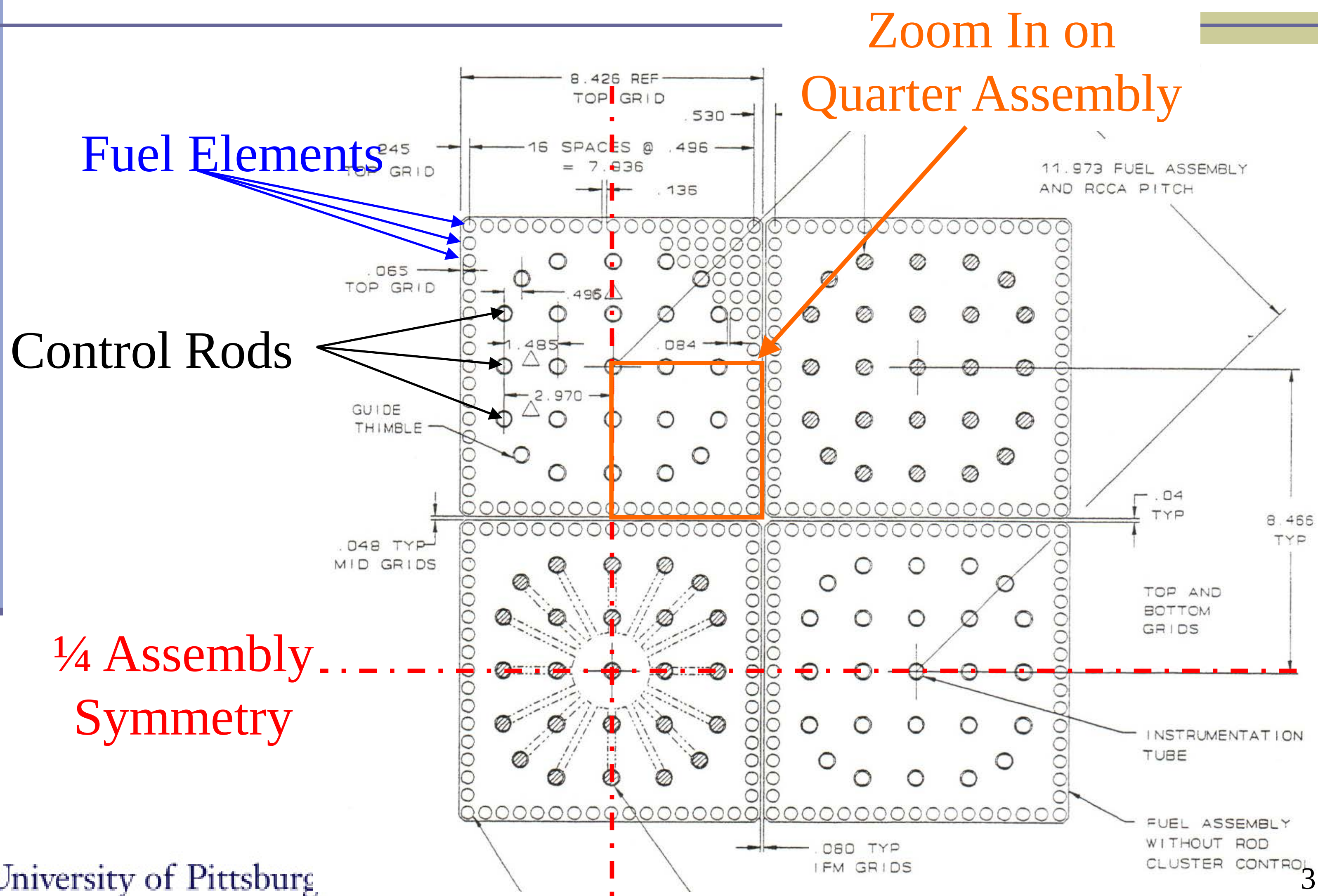
PWR (W & B&W) Control Rod "Spider"



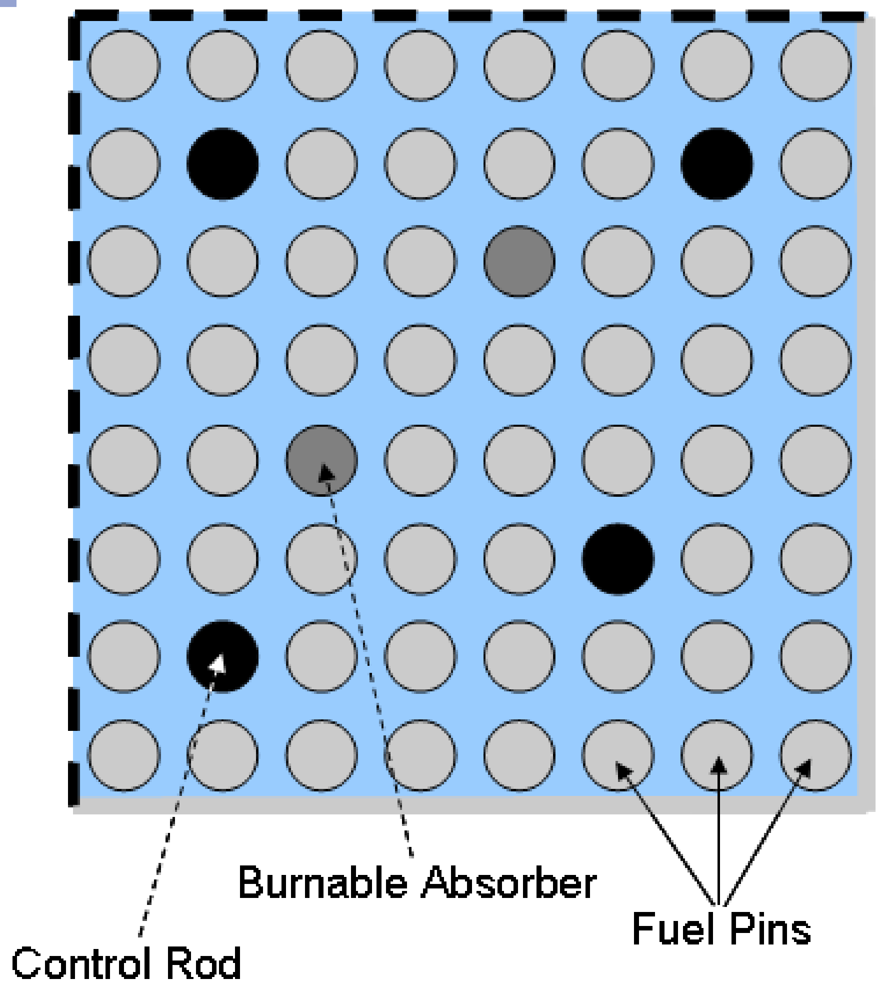
AP600 Core Design



AP600 Assembly Design

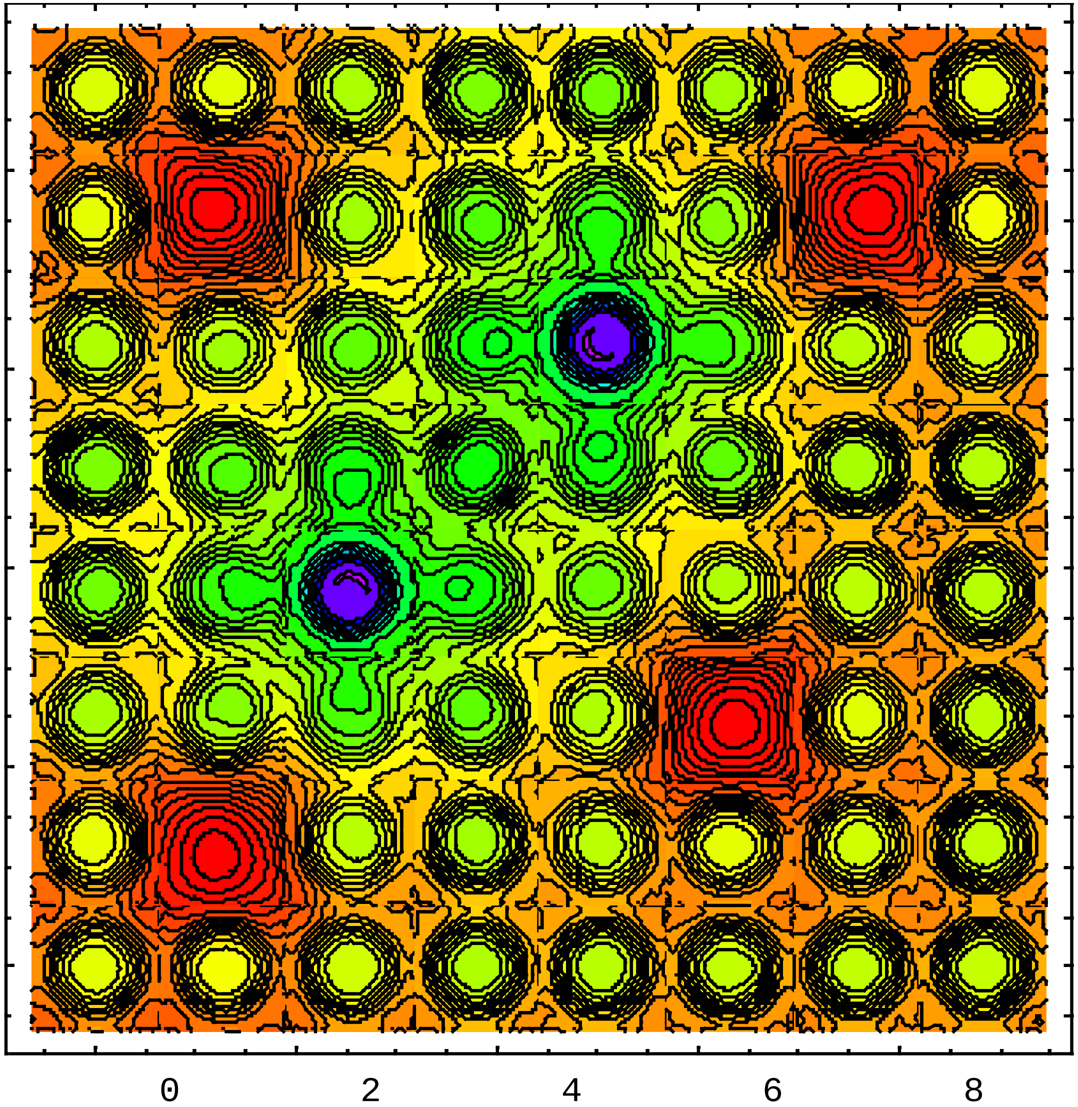


Simplified AP600 Assembly Model



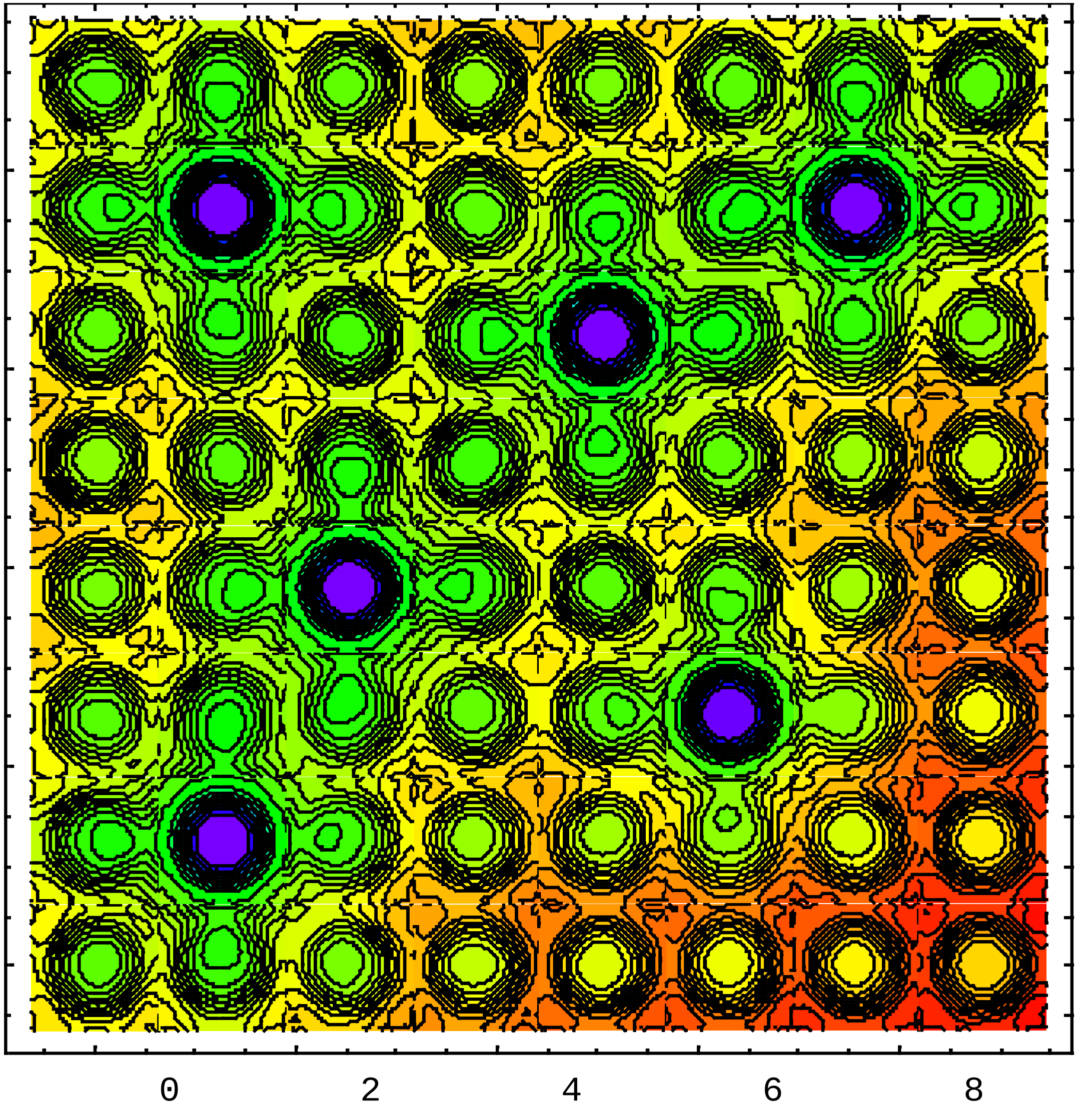
- Simplified 2-D model of an AP600 quarter assembly.
- Contains UO_2 fuel, boron control rods, and B4C burnable absorber rods.
- Reflecting boundary conditions on all sides.

Quarter-Assembly, Control Rods Withdrawn



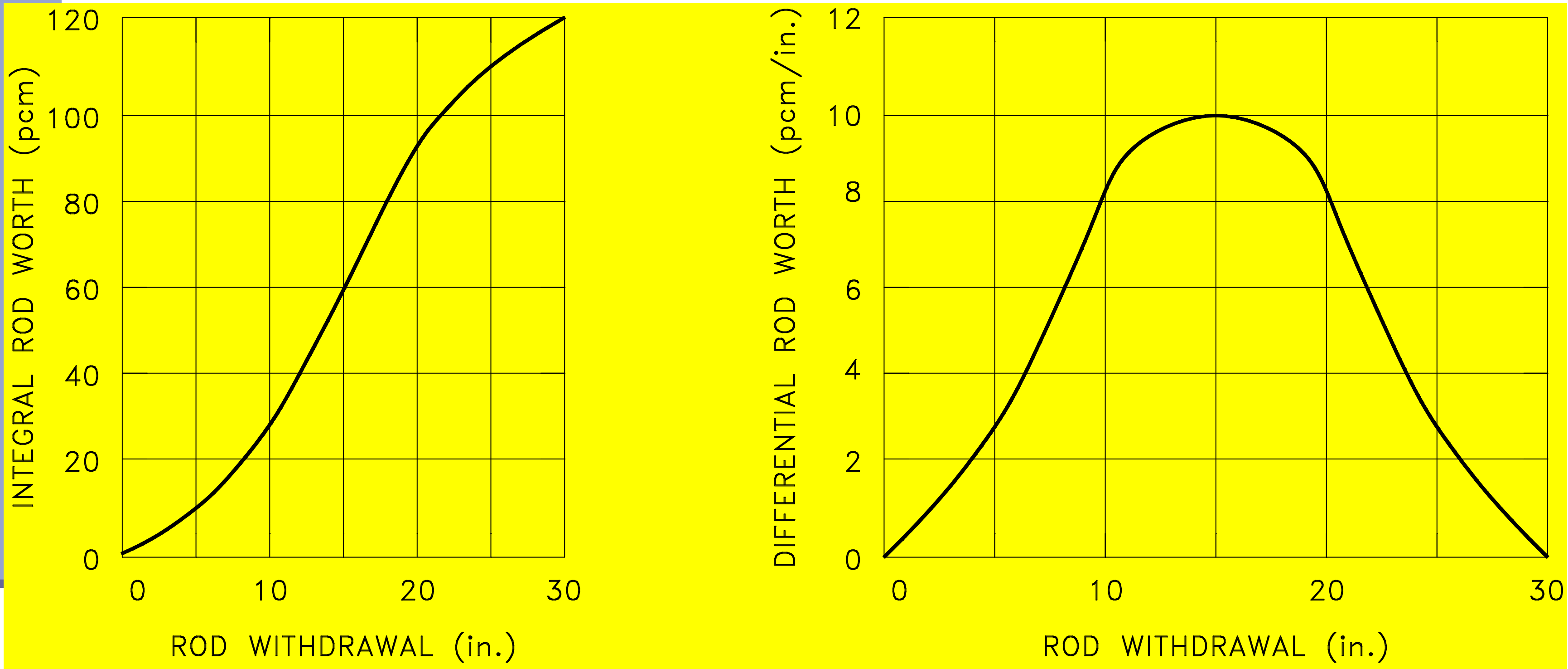
$k = 1.1630$

Quarter-Assembly, Control Rods Inserted

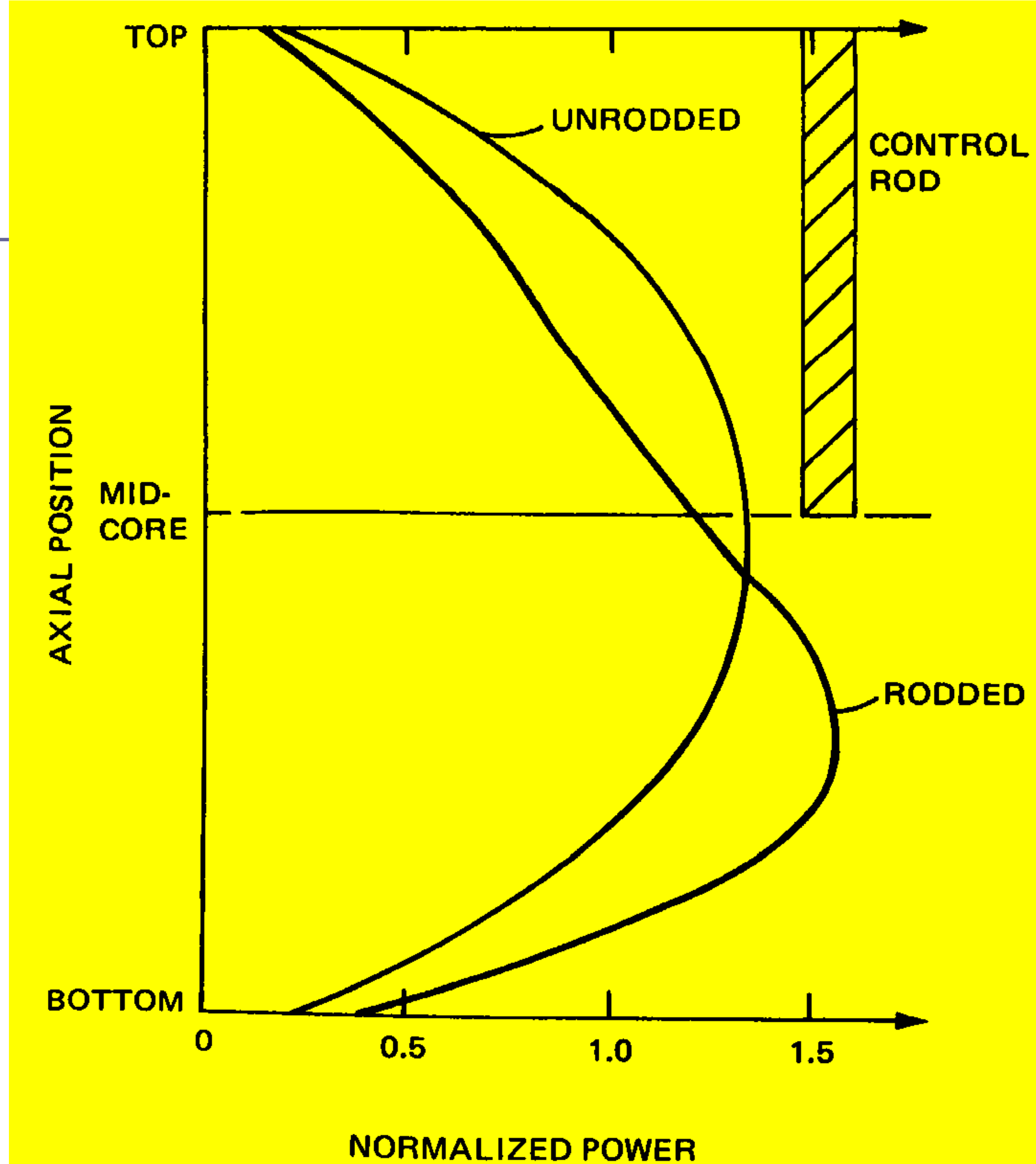


$k = 0.93287$

Control Rod Worth Example



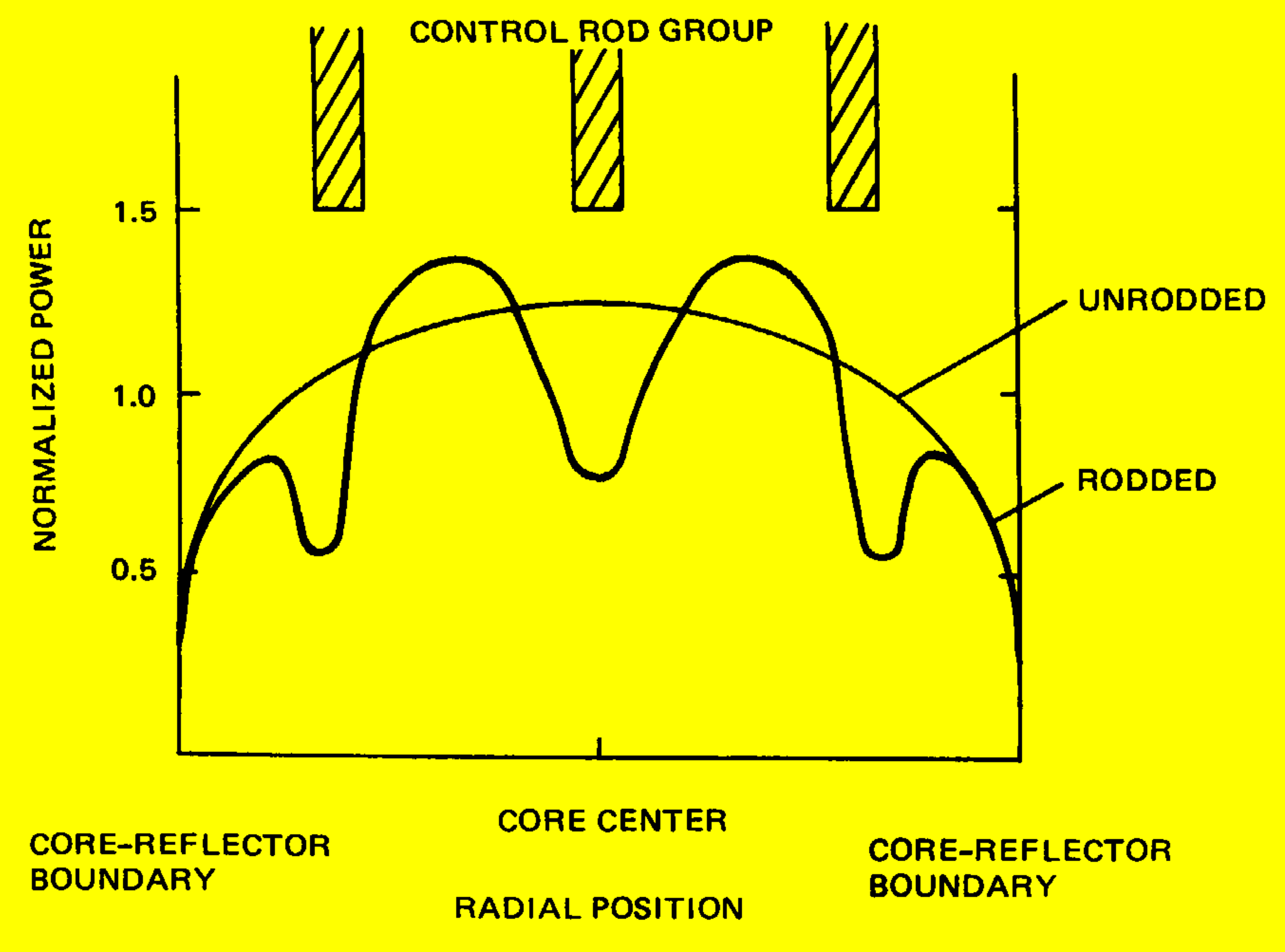
Axial Flux w/ Control Rods



Delta I - Power Shape Distortion

- ΔI = Upper Power - Lower Power
- Want to keep the axial power shape well conditioned
- We move control rods to control the axial power shape
  - Prevent axial power peaks

Radial Flux w/ Control Rods



PWR Reactivity Control

- Routine Control Rod Adjustment for Critical
  - Full Safety/Control Rod Insertion [Scram/Trip]
    - Overpower
    - Other Parameters Out of Range
- Intermediate / Long-Term
  - Soluble Poison – Boric Acid
    - Minimize Control Rod Use
    - ~25% Group-1 Bite at Full Power
    - Decreased w/ Burnup
    - Changed w/ Steady Power Change
  - Burnable Poison [Shim] Rods

PWR Protective System

- SCRAM / TRIP
  - Full-Length CR Mounted to Drives w/ Electromagnets
  - Loss-of-Current → Full Insertion
- REACTIVITY INVENTORY
  - Control Rods
  - Negative Feedback Defects
  - Shutdown Margin - Several %Δk/k
    - Stuck Rod Criterion - Highest Worth
    - Over Core Lifetime

FEEDBACK EFFECTS

- COEFFICIENTS OF REACTIVITY α

$$\alpha(T_i) = \frac{\partial \rho}{\partial T_i}$$

$T_i \rightarrow T_f$ Fuel Temperature Coefficient [FTC]

T_m Moderator Temperature Coefficient [MTC]

f_v Moderator Void Coefficient [MVC]

d_m Moderator Density Coefficient [MDC]

$$feedback\ reactivity = \Delta\rho_F = \sum_i \alpha(T_i)\Delta T_i = \sum_i \frac{\partial \rho}{\partial T_i}\Delta T_i$$

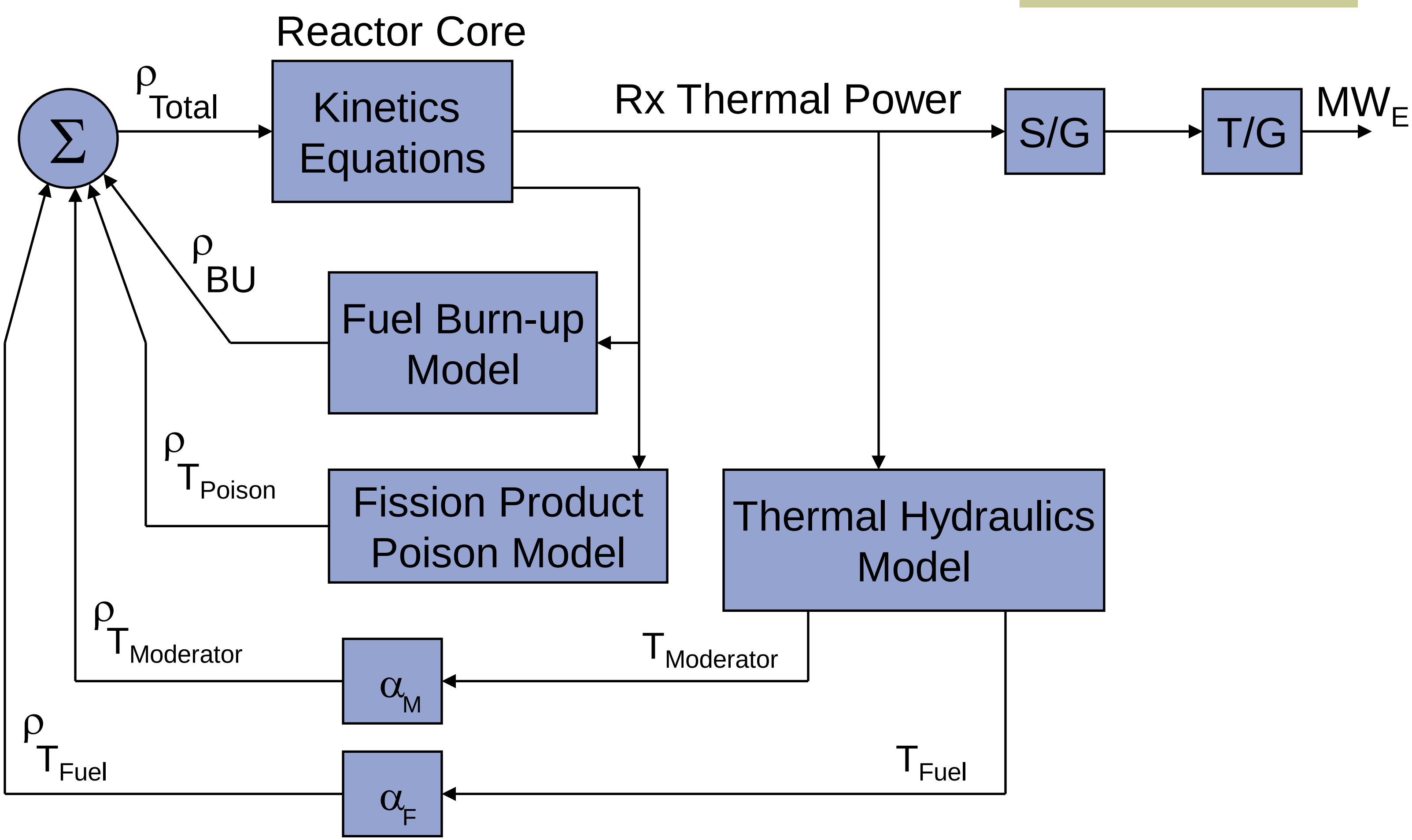
INTEGRATED SYSTEM RESPONSE

- FEEDBACK LOOP
  - $\Delta\rho_{EXT}$ Inserted
  - Power $\dot{Q}_{Rx}$ from Kinetics Equations
  - ΔT & ΔDensity $\rightarrow$ Feedback Reactivity $\Delta\rho_F$
    - $\Delta\rho_{EXT} + \Delta\rho_F = \Delta\rho_{TOTAL}$

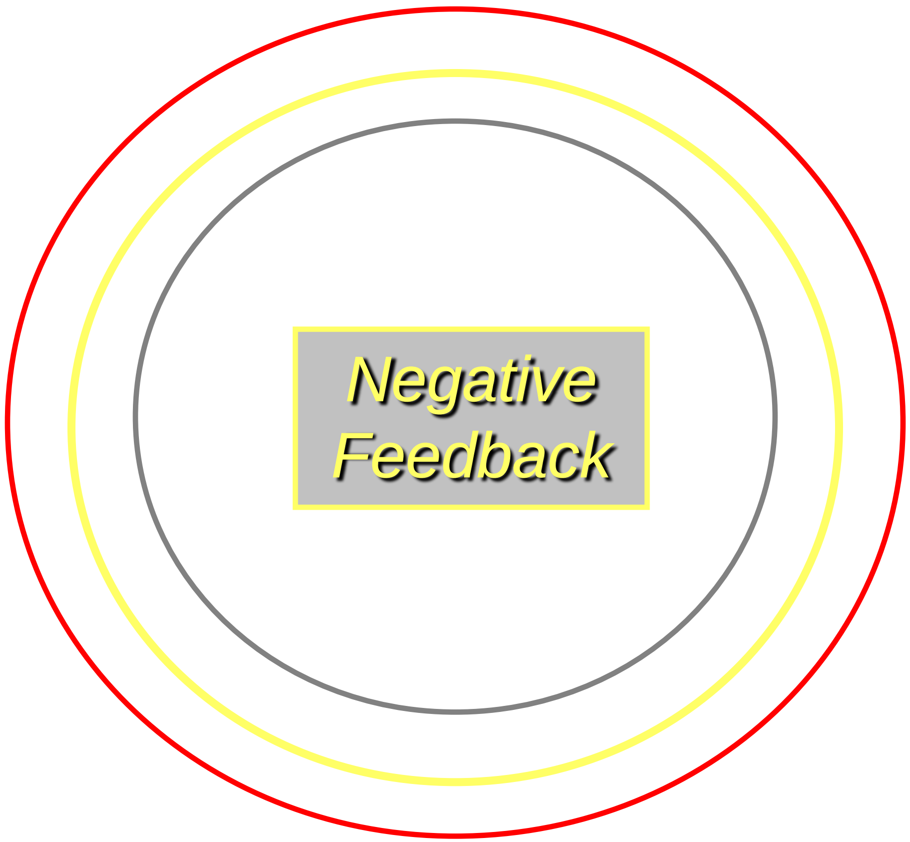
If $\Delta\rho_{TOTAL} < \Delta\rho_{EXT}$ $\rightarrow$ Stabilization

If $\Delta\rho_{TOTAL} > \Delta\rho_{EXT}$ $\rightarrow$ Unstable $\rightarrow$ Possible System Damage, If Uncompensated

Inherent Reactivity Effects



Negative Reactivity Feedback Effect



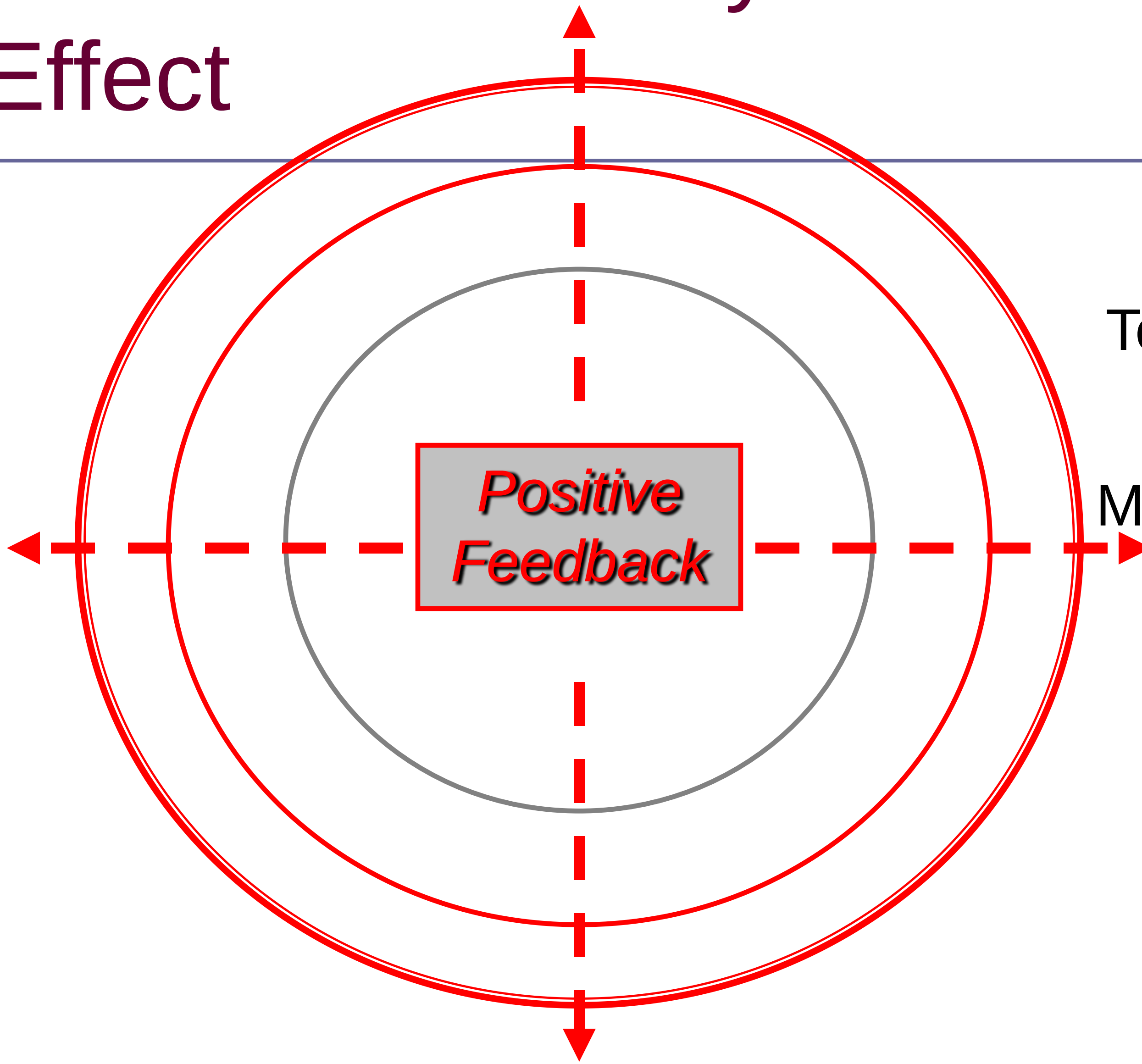
Power ⇑ ⇓

Temperature ↑ ↓

Multiplication ↓ ↑

Resists the Effect That Produced It & Is Stabilizing

Positive Reactivity Feedback Effect



Power ⇑ ⇑

Temperature ↑ ↑

Multiplication ↑ ↑

Enhances the Effect That Produced It & Is Destabilizing

Fission Product Poisoning - Xenon

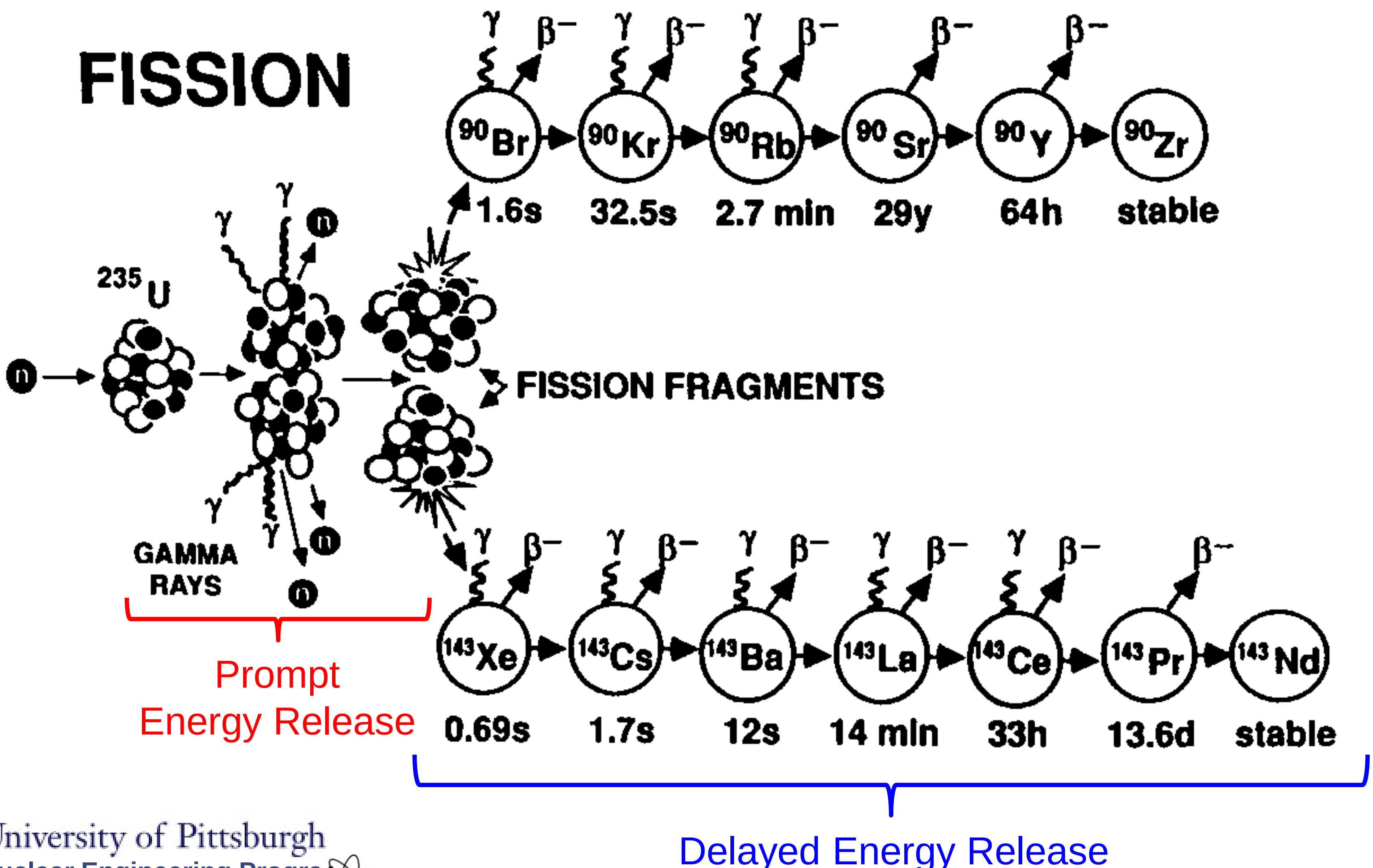
We get fission products from the fission process (the ashes of burning uranium)

- Hundreds of various fission products
- All chemical species
- All physical forms

- Some fission products have very large probability to absorb neutrons

When these fission products are present in the reactor, they can have a very strong effect on reactivity, ρ

Fission Products (the ashes) Released During Fission



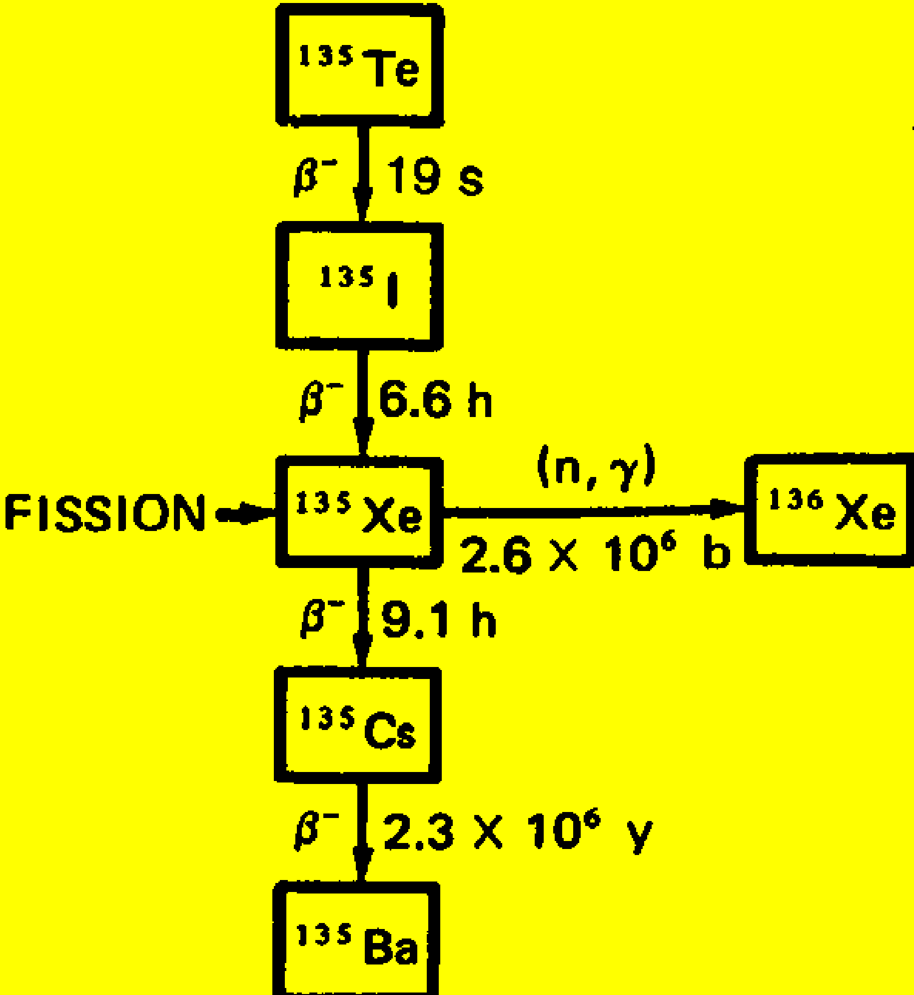
Fission Product Poisoning - Xenon

- When a new reactor with fresh fuel starts up, poisoning by xenon is not evident until some Xe has formed.
- Xe builds up to an equilibrium level and absorbs neutrons.
- When the reactor is shut down, it goes through a peaking transient that can affect the ability to restart the reactor.

Fission Product Poisoning - Xenon

- Production of Xenon-135
- Produced in two ways:
  - As a daughter in a radioactive decay chain (from Iodine-135,
  - As a direct yield from fission
- Lost in two ways:
  - By radioactive decay,
  - By absorption of a neutron to become Xe-136 (weak absorber)

^{135}Xe Production



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

FISSION PRODUCTS

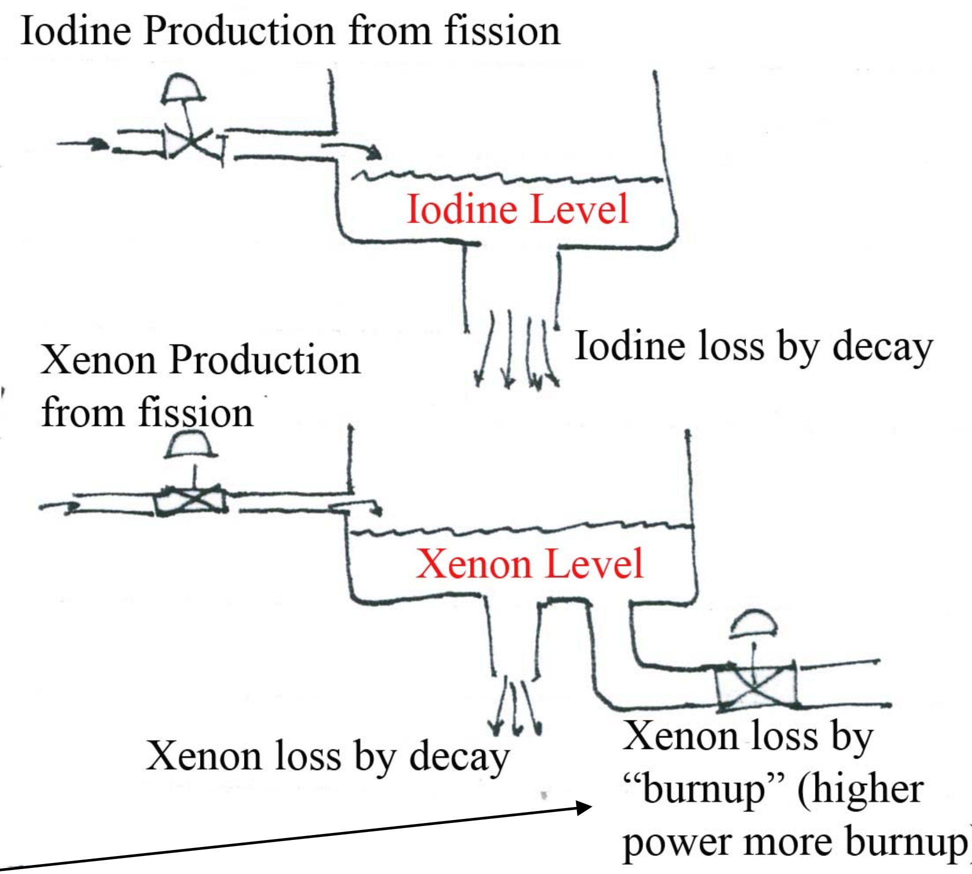
- XENON-135 Production (P) and Destruction

$$\left\{\begin{array}{l} Rate\ of\ \ change \\ of\ \ Xenon \end{array}\right\} = \left\{P_{Xenon} + Decay_{Iodine}\right\} - \left\{Burnup_{Xenon} + Decay_{Xenon}\right\}$$

$$\left\{\begin{array}{l} Rate\ of\ \ change \\ of\ \ Iodine \end{array}\right\} = \left\{P_{Iodine}\right\} - \left\{Decay_{Iodine}\right\}$$

The Transient Xenon Problem

Here it is in a picture:



But there are other things going on:

1. Production processes from fission which we represent as a valve whose opening is proportional to the flux (power) level.
2. Burnup loss goes to zero if power (flux) goes to zero.

Fission Product Poisoning - Xenon

Major Points to note:

1. Xenon effects will be felt over relatively long time intervals (since Xe and I decay so slowly).

2. Production of Xenon is from Iodine decay and direct fission yield.

3. Iodine decays faster than Xenon

Effect of Xenon on Reactivity

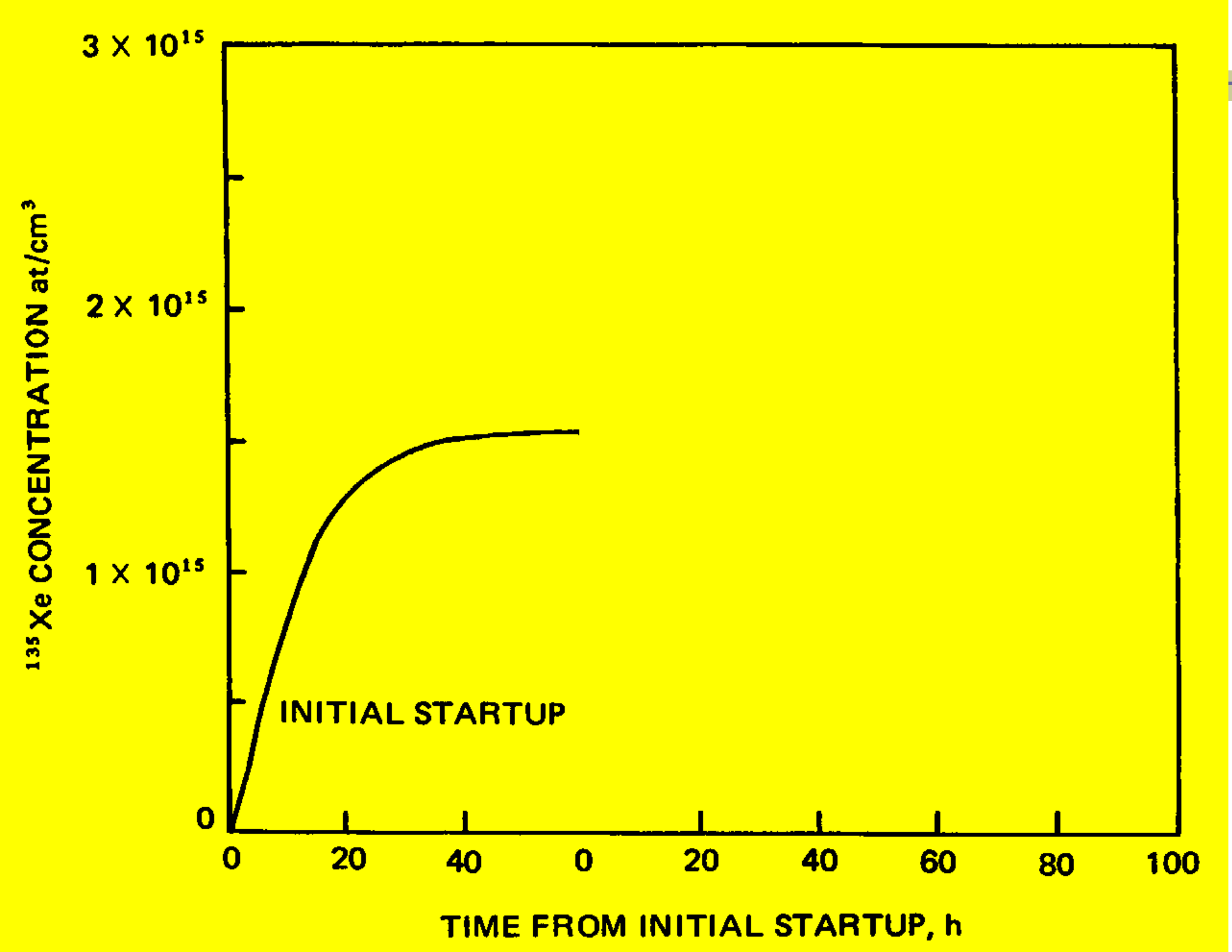
What does this mean when we operate a reactor?

1. We start up a new reactor. It is xenon-free.
2. We go critical at low power (low flux) - negligible xenon
3. We bring the reactor to high power
4. As xenon builds up, we have to withdraw control rods to stay critical

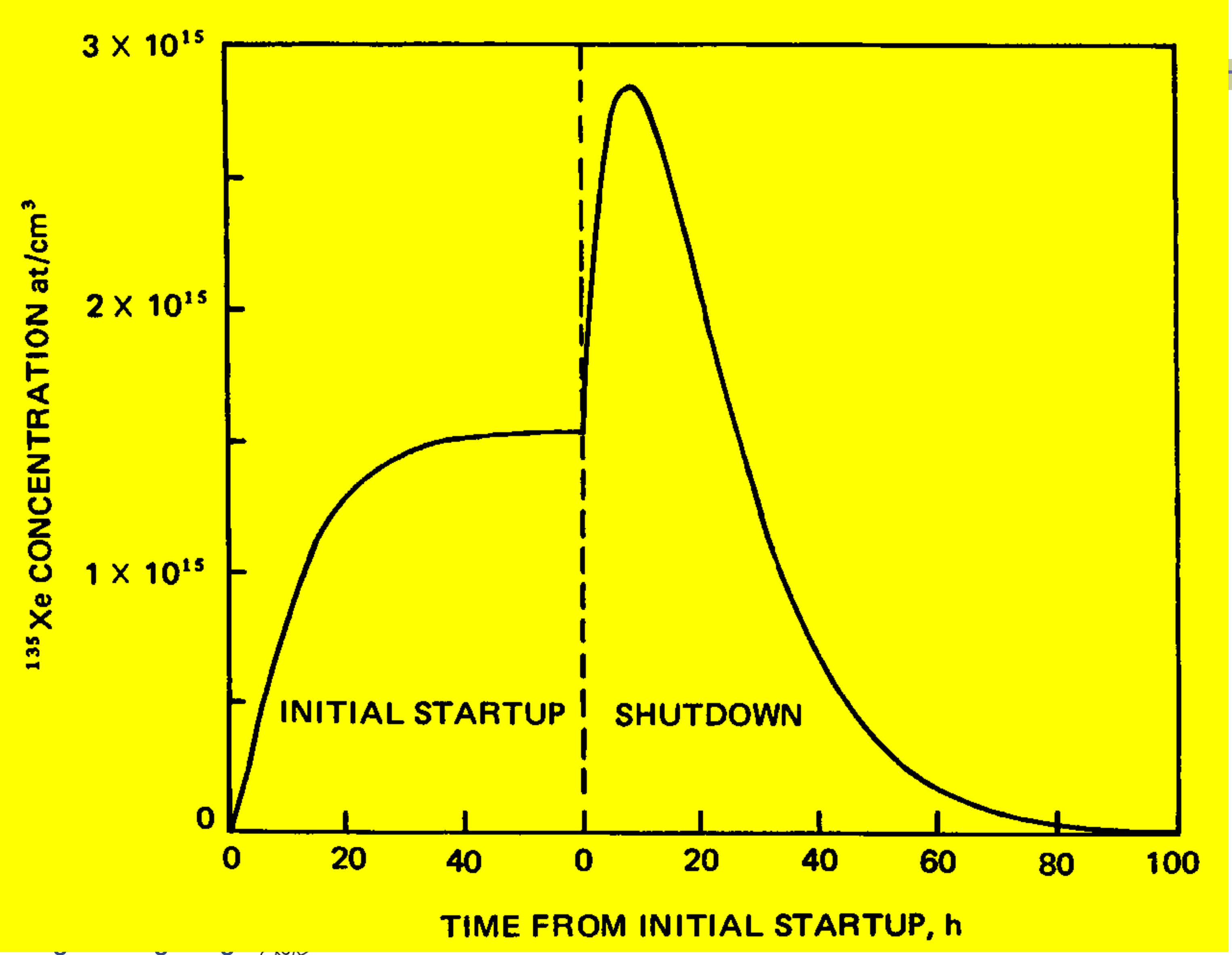
Xenon reactivity worth could be on the order of

$$\rho_{Xe} \approx -0.024 = -24mk$$

^{135}Xe Behavior



^{135}Xe Behavior



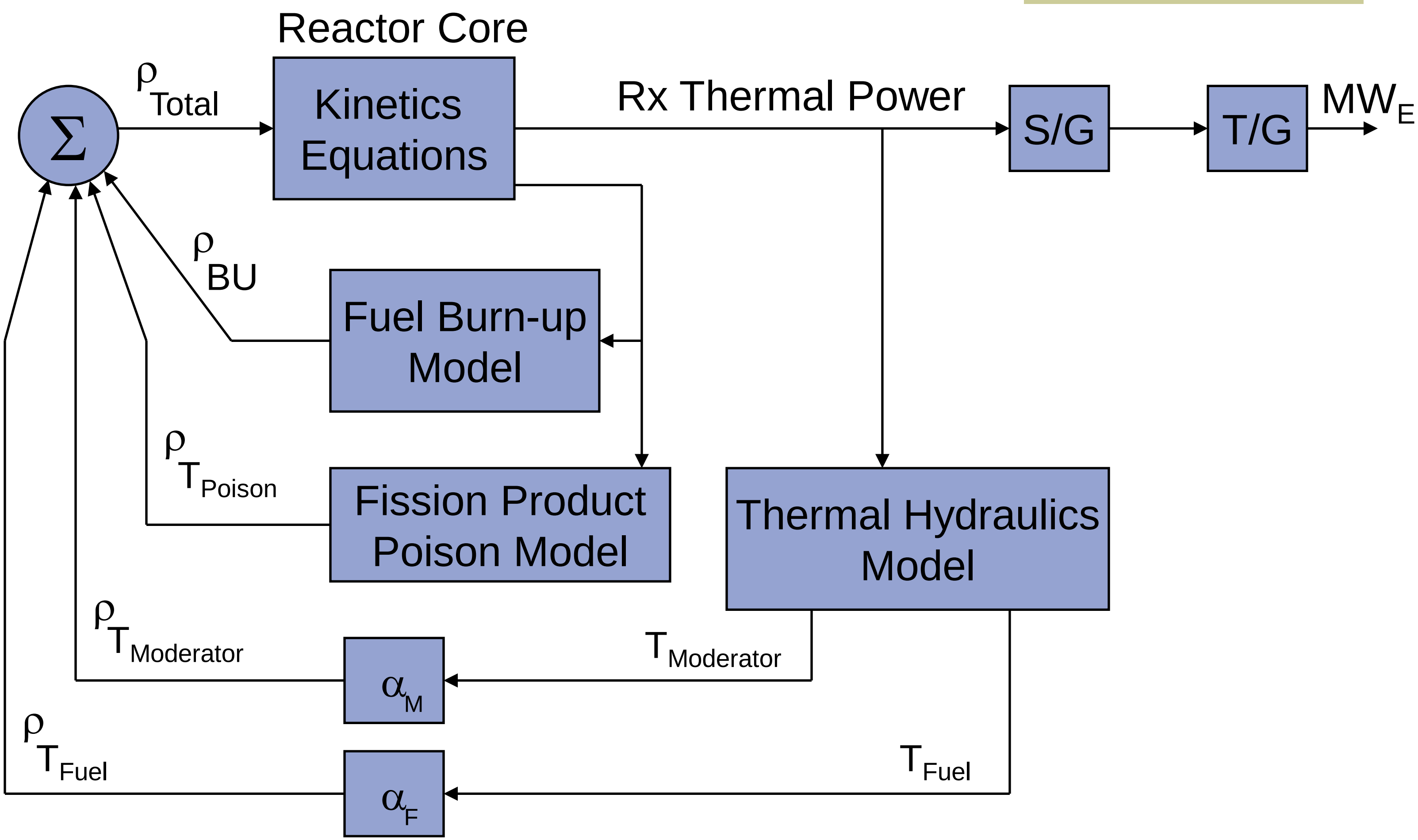
OPERATIONAL IMPACTS

- LONG-TERM REACTIVITY CONTROL
  - Programmed Control Rod Motion
    - Change Power Level
      - Startup / Shutdown
      - Load Follow
      - Re-Start
    - Withdraw to Compensate Fuel Burnup
    - Damp Xenon Oscillations
    - Concern $\rightarrow$ Power Peaking

OPERATIONAL IMPACTS

- LONG-TERM REACTIVITY CONTROL
  - Soluble Poisons
    - Inject / Dilute to Match Power Level
    - Dilute to Compensate Fuel Burnup
    - Reduce Control Rod Use
    - Concern $\rightarrow$ Positive Coolant/Moderator Feedback

Inherent Reactivity Effects



External Reactivity Effects by Protection and Control Systems