University of Pittsburgh

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Fission Reactor Basics:

Criticality Control

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Relevant Reading Assignments

- Sections 6.5 to 6.8 of "*Introduction to Nuclear Engineering*" by Lamarsh and Baratta, 3rd Edition.
- Chapter 3 of "*Nuclear Reactor Analysis*" by Duderstadt and Hamilton
- Page 100-120 of "*Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*" by Knief, 2nd Edition.

Relevant Reading Assignments

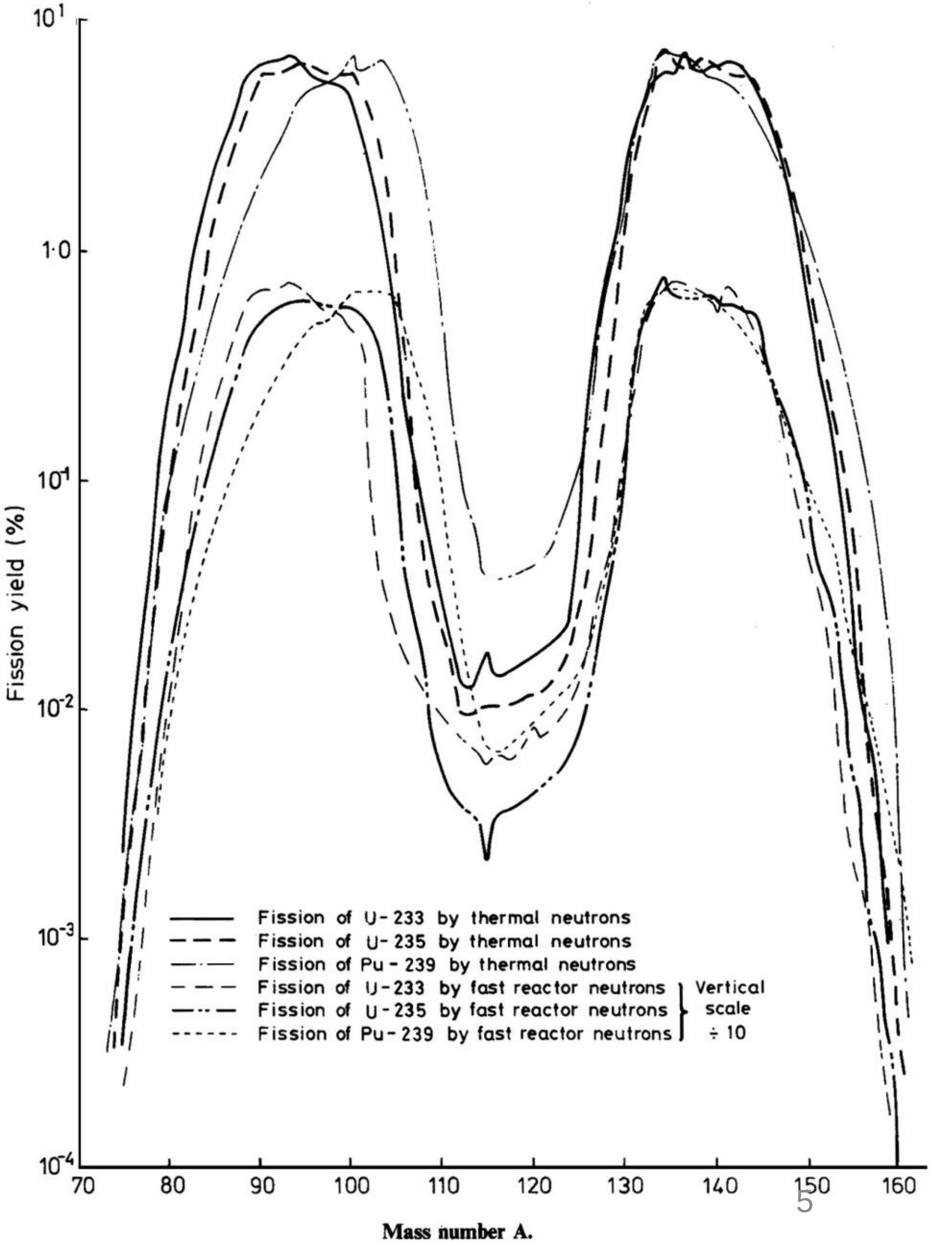
- "Secrecy, simultaneous discovery, and the theory of nuclear reactors" by Spencer Weart. American Journal of Physics, Vol. 45(11). November 1977

Learning Objectives

- Explain how the terms in the four and six factor formulas may be adjusted to control criticality in reactor and processing settings

Criticality Control

- No reactor can be constantly critical
- Fuel depletion
  - Fission removes a fuel atom and creates two new atoms
  - Transient fission product poisons
    - Xenon and Samarium
  - Fission product poison build up
    - 83Kr, 95Mo, 143Nd, 147Pm
- Temperature (moderator density) changes



Creating Neutron Balance

- States of criticality

keff = 1	Critical
keff > 1	Supercritical
keff < 1	Subcritical

- 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

Creating Neutron Balance

- Let us consider how we could adjust these parameters to achieve a target keff for two different applications

- Nuclear Power Plant
  - Target keff:
    - keff = 1 for steady-state operation
    - keff > 1 for start-up, keff < 1 for shutdown

- Nuclear Fuel Processing Facility
  - Target keff:
    - keff < 1 under all possible conditions (including accidents)

Neutron Balance (Reactor)

- Reactor Criticality Requirements
  - Operation Modes
    - Power Reactors (Startup / Steady-State / Shutdown)
    - Some Research Reactors (Pulse Mode)
    - All reactors have emergency shutdown (SCRAM) 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.

Neutron Balance (Reactor)

- Nuclear Reactor
  - **Production**
    - Determined by the total fissile content of the core.
    - Initial fuel loading.
    - Conversion of fertile nuclides (breeding).
    - Refueling
      - On-line or Shutdown

Neutron Balance (Reactor)

- Nuclear Reactor
  - **Production**
    - For a modern commercial PWR core:
      - Ceramic UO_2 pellets using Uranium that has been enriched to 3-5 wt % ^{235}U.
      - 10-30% of power produced in a PWR is due to Plutonium bred in the reactor
      - Currently reactors operate 18-24 months between refuelings

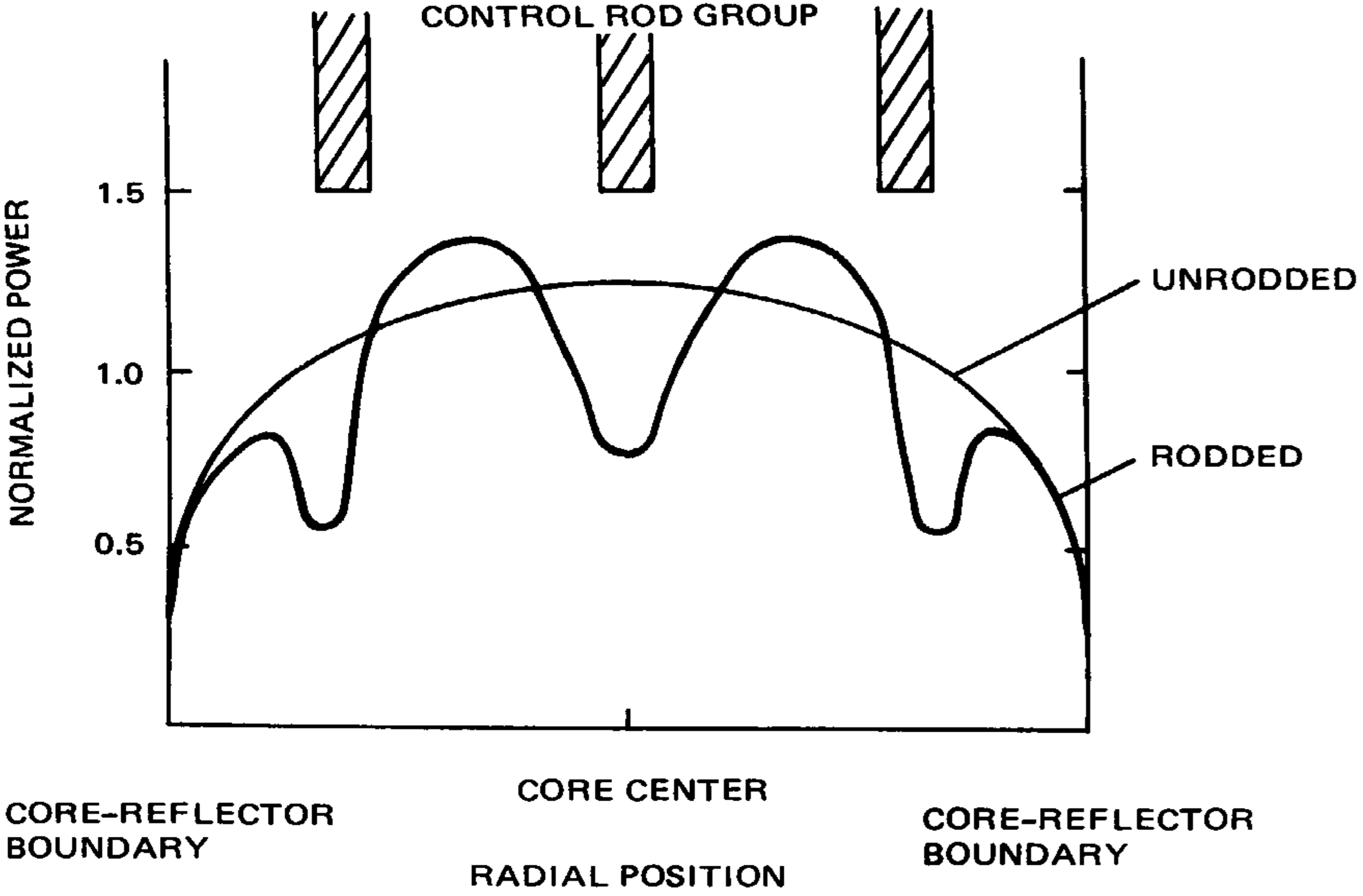
Neutron Balance (Reactor)

- Nuclear Reactor
  - **Absorption**
    - Cladding, Structure, Coolant
    - Control Rods
    - Soluble Poisons
    - Burnable Poisons
    - Fission-Product Poisons

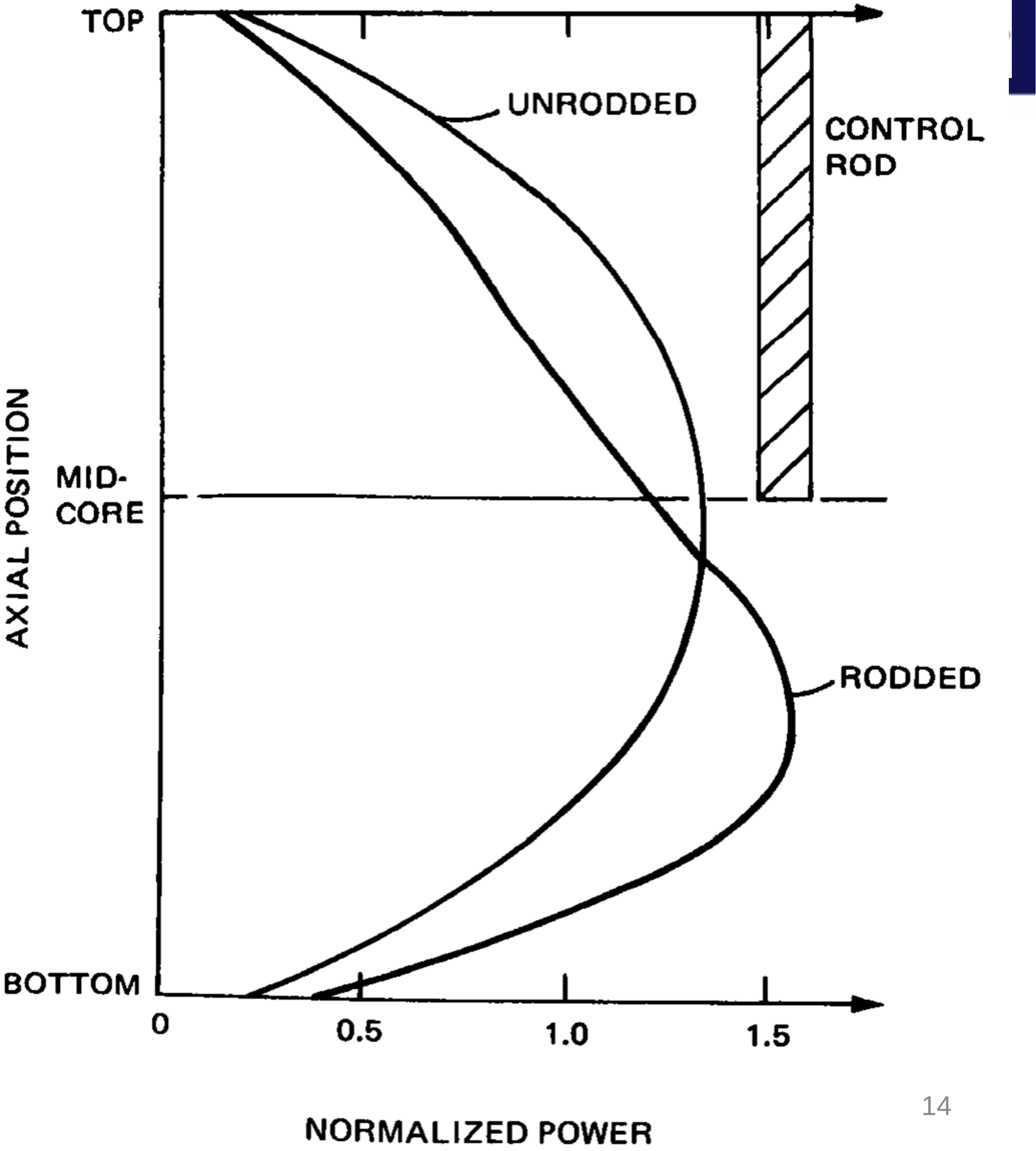
Neutron Balance (Reactor)

- Nuclear Reactor
  - 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} (like trim control in an airplane).
      - Fixed burnable poisons (boron or gadolinium) that deplete during operation.

Radial Flux w/ Control Rods



Axial Flux w/ Control Rods



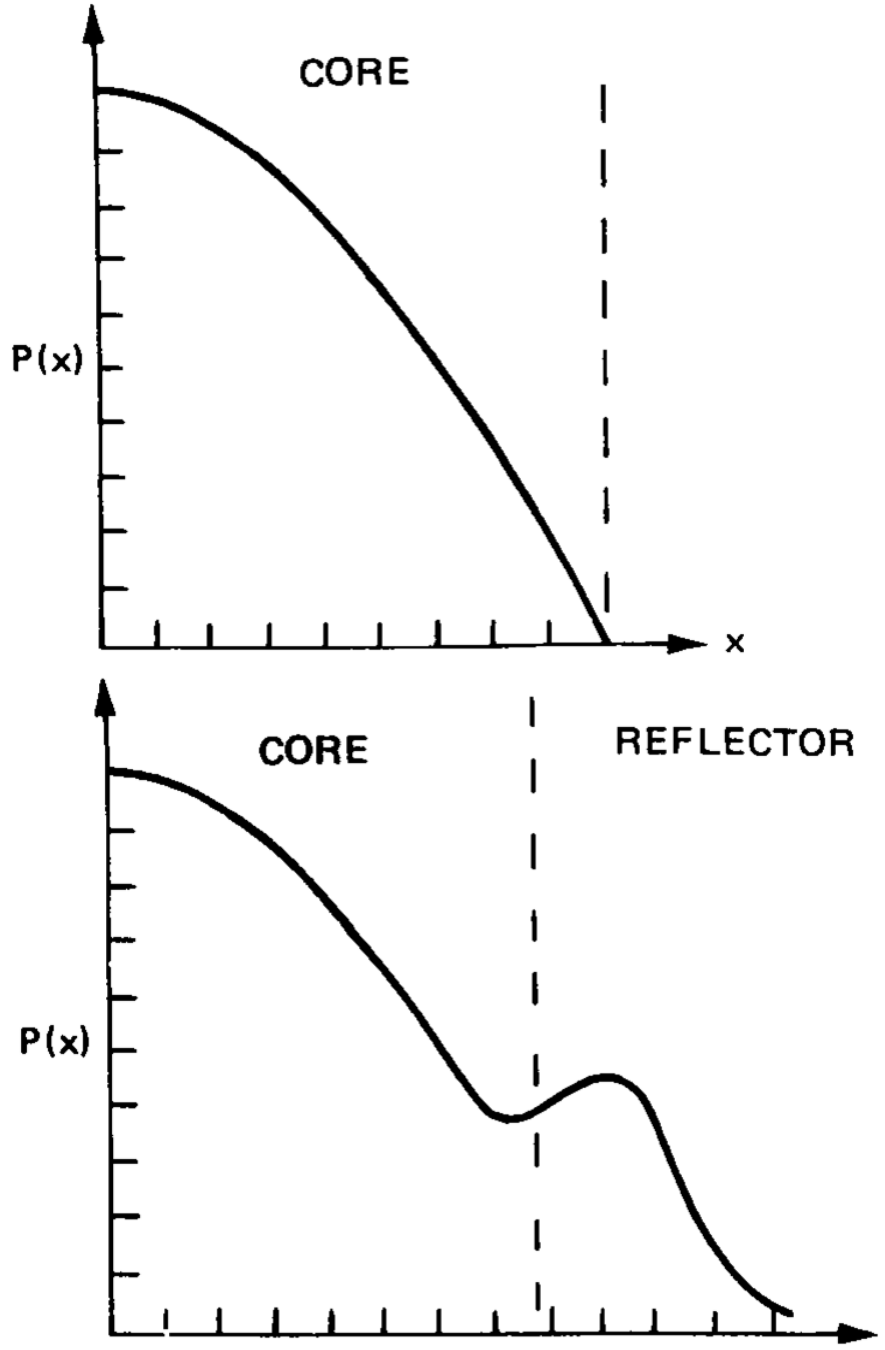
Neutron Balance (Reactor)

- Nuclear Reactor
  - **Leakage**
    - Core size and shape
    - “Reflection” of neutrons back into the core
    - Density of core material(s)
      - (temperature-dependent)

Neutron Balance (Reactor)

- Nuclear Reactor
  - 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

Water-Reflector Effect on Minimum Core Size



Neutron Balance (Reactor)

- Nuclear Reactor
  - ***Moderation***
    - Controls how effectively neutrons can slow down to thermal energies.
    - Determined by selection of moderator material and pin dimensions (diameter and pitch)

Neutron Balance (Reactor)

- Nuclear Reactor
  - ***Moderation***
    - In modern PWR designs
      - Light water (H_2O) is used as both moderator and coolant
      - Pin diameter: $\approx$1 cm
      - Pin pitch: $\approx$1.25 cm

Neutron Balance (Fuel Facility)

- Fuel Facility
  - Always Subcritical!
    - Designed subcritical, no required adjustments
      - Verify that current configuration is subcritical
      - Confirm that proposed changes will be subcritical
    - $k_{\text{eff}} < 1$ under all conditions
      - Must account for:
        - » Uncertainties in Experimental Data and Calculations
        - » Normal, Anticipated Abnormal & Credible Accident Scenarios

Criticality Control (Fuel Facility)

- Fuel Facility
  - **Production**
    - Determined by the total fissile content present in a single location.
    - Must consider the mass, enrichment, and concentration (density) of fissile materials.
    - Fuel handling sites have strict limits on these quantities to prevent accidents.

Neutron Balance (Fuel Facility)

- Fuel Facility
  - **Absorption**
    - Non-Fissile Materials (Enrichment)
    - Non-Fissionable Materials
    - Solid Poisons
    - Soluble Poisons

Neutron Balance (Fuel Facility)

- Fuel Facility
  - **Leakage**
    - Density
    - Favorable Geometry
      - High Leakage (Long Cylinder/Thin Slab)
      - Individual Unit Subcritical
    - Reflection
    - Separation of Units

Neutron Balance (Fuel Facility)

- Fuel Facility
  - ***Moderation***
    - Affects
      - Production
      - Absorption
      - Leakage
    - Important factor in complex interactions between: spacing, absorption, and moderation among units

Beyond 4 & 6 Factor Formulas

- The four factor formula gives us a good way to examine the competing bulk neutron balance effects in an infinite system.
- In finite systems, neutron leakage must be included when determining the overall neutron balance for the system.
- When designing critical systems (reactors) we need to know the spatial distribution of neutrons in the core, in addition to the multiplication factor.

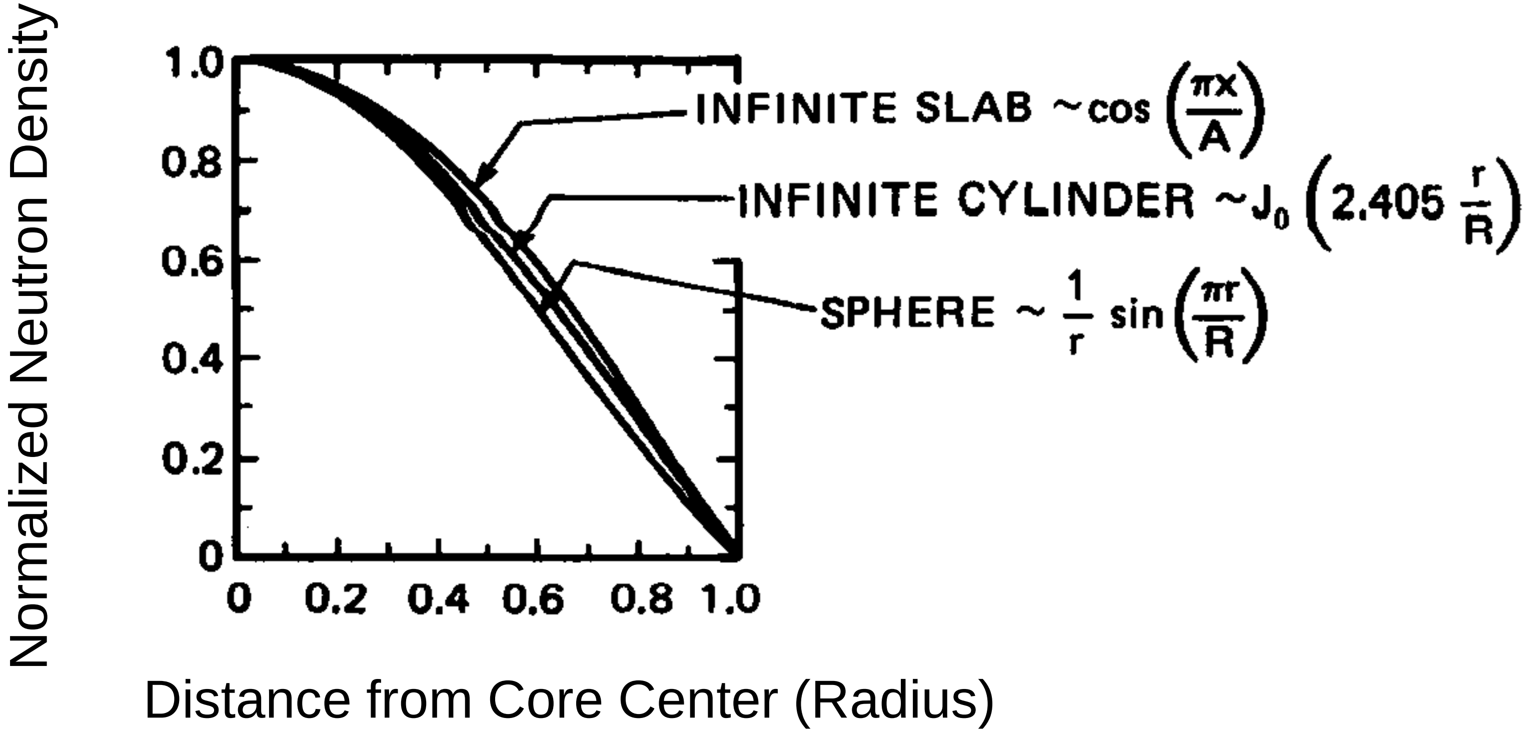
Beyond 4 & 6 Factor Formulas

- In a large reactor, different parts of the core may be behaving very differently
  - Outer regions of the core will have a large amount of neutrons escaping from the core, and will be losing a large fraction of neutrons than are born within the region.
  - Neutrons produced in inner regions of the core have little chance of escaping the core. These inner regions will effectively produce more neutrons than are needed locally for fission.
- For the reactor as a whole to be critical, these local regions must balance each other out.
  - Different concentrations of neutron densities and reaction rates throughout the core.
  - Neutrons “flow” from the center of the core towards the edge.

Neutron Density

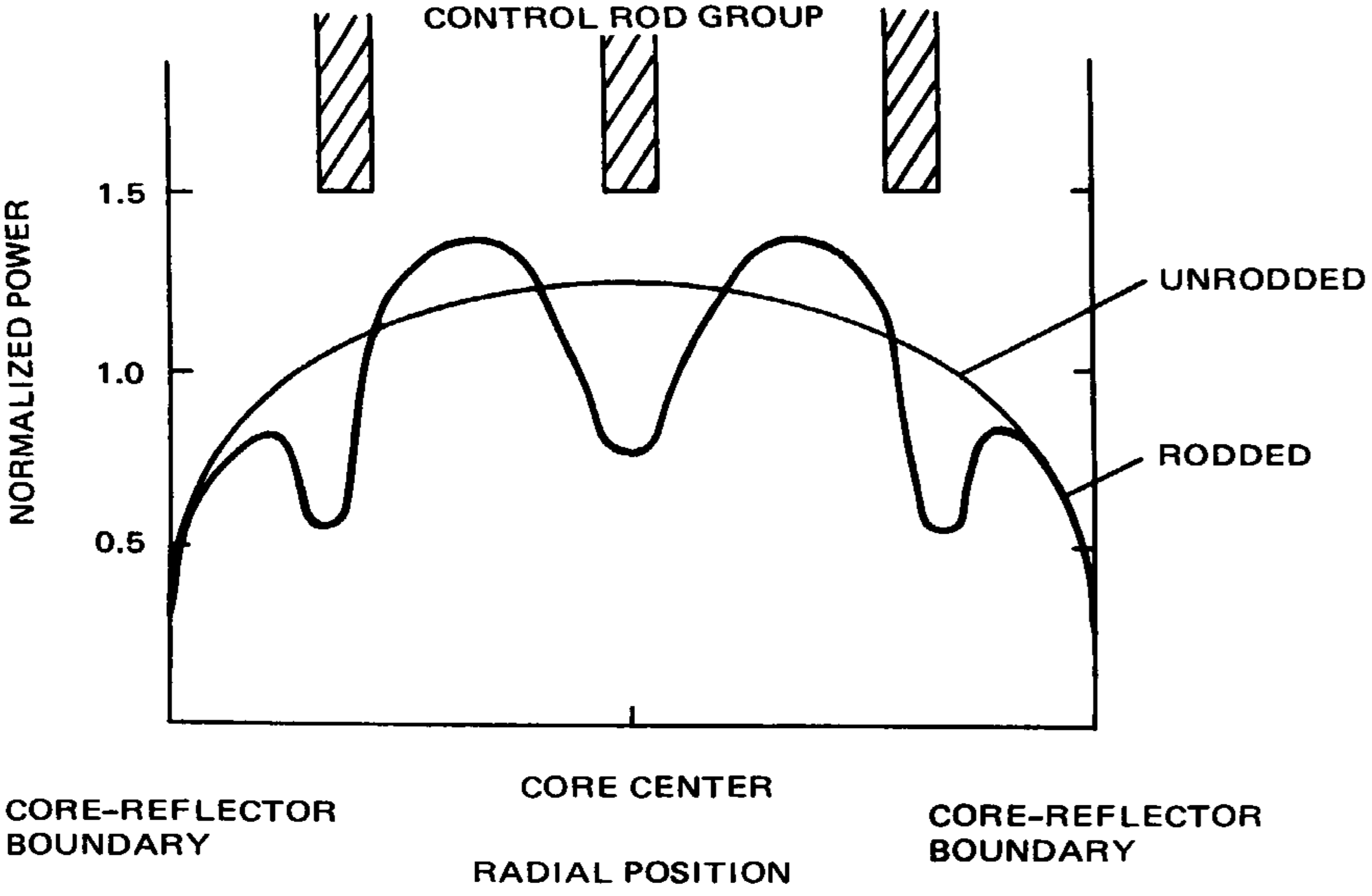
- During steady-state operations there is a natural spatial distribution of neutrons throughout the core.
- This natural distribution depends on the shape of the reactor and the locations of fissile fuel and neutron poisons in the core
  - Peaked in center
  - Low near edge of core
  - Low density near neutron poisons
- In addition to the gross shape of the neutron density, there are local variations that can have a significant effect on the behavior of the core
  - Localized peaking is usually limiting condition in core

Neutron Densities by Geometry

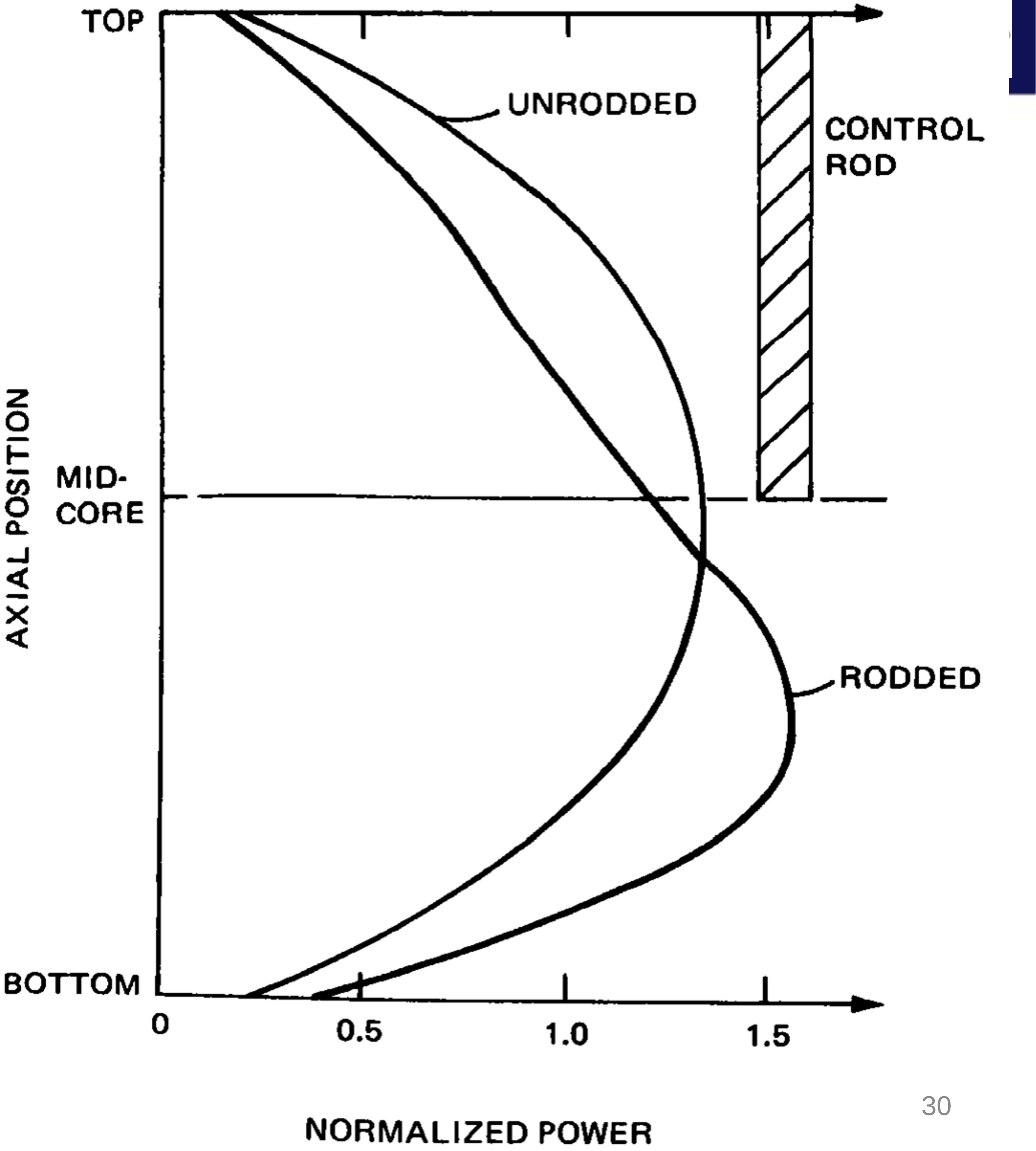


- All Three Neutron Densities are “Cosine-Like”
- Peaked in the Center
- Zero at the Edges

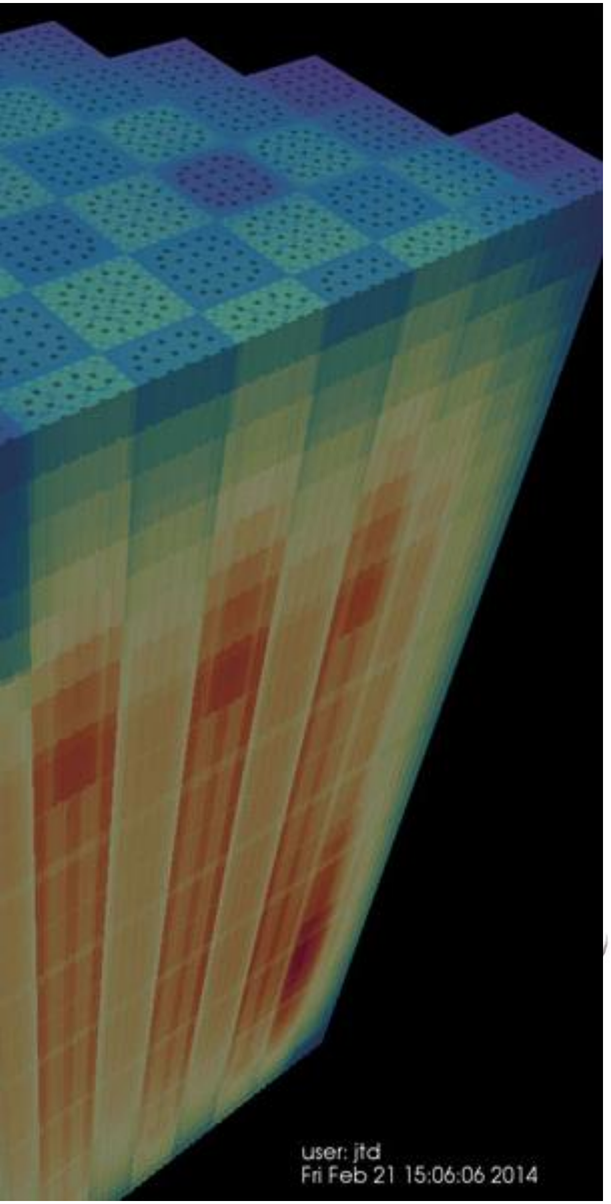
Radial Neutron Density

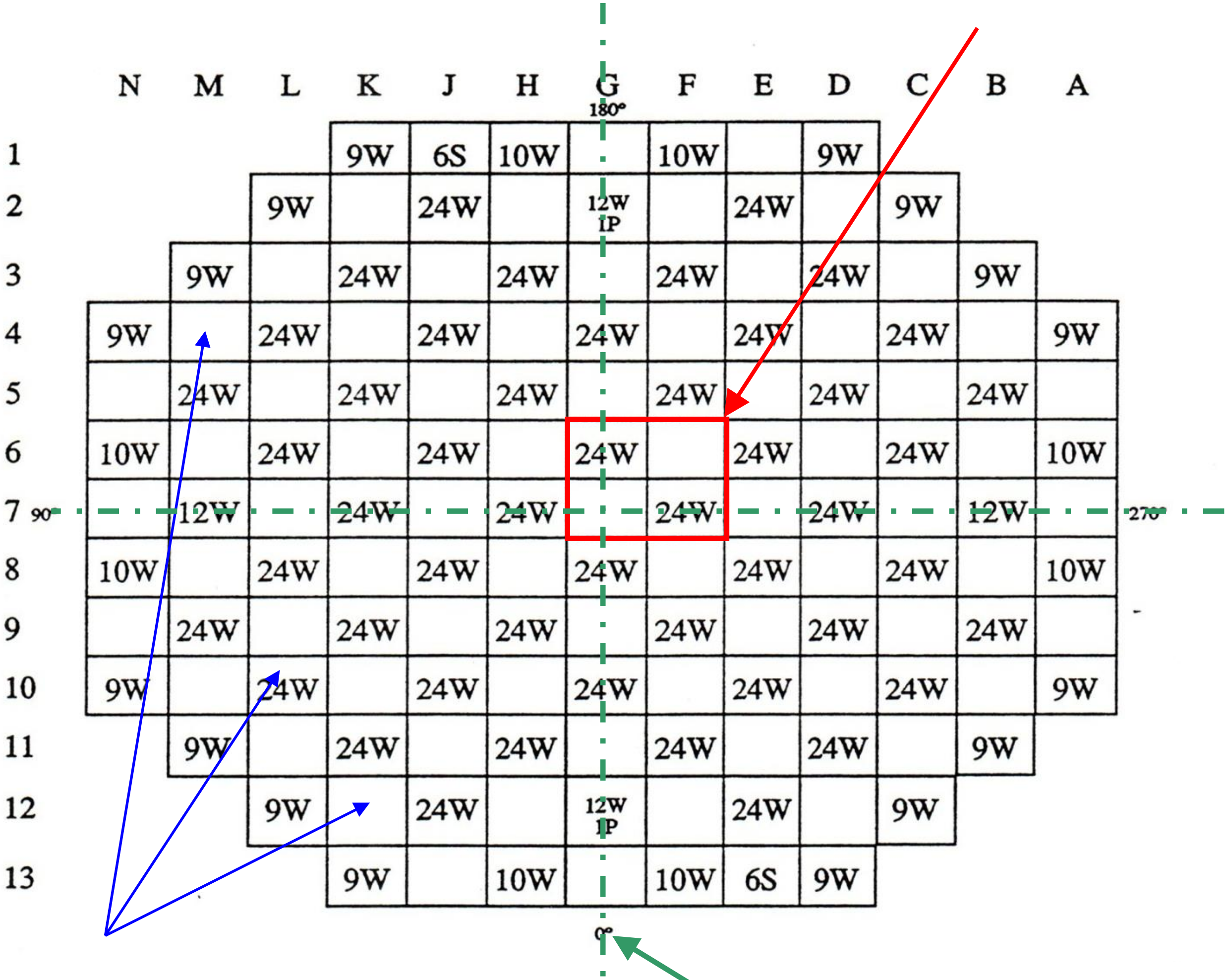


Axial Flux w/ Control Rods



AP600 Core Design





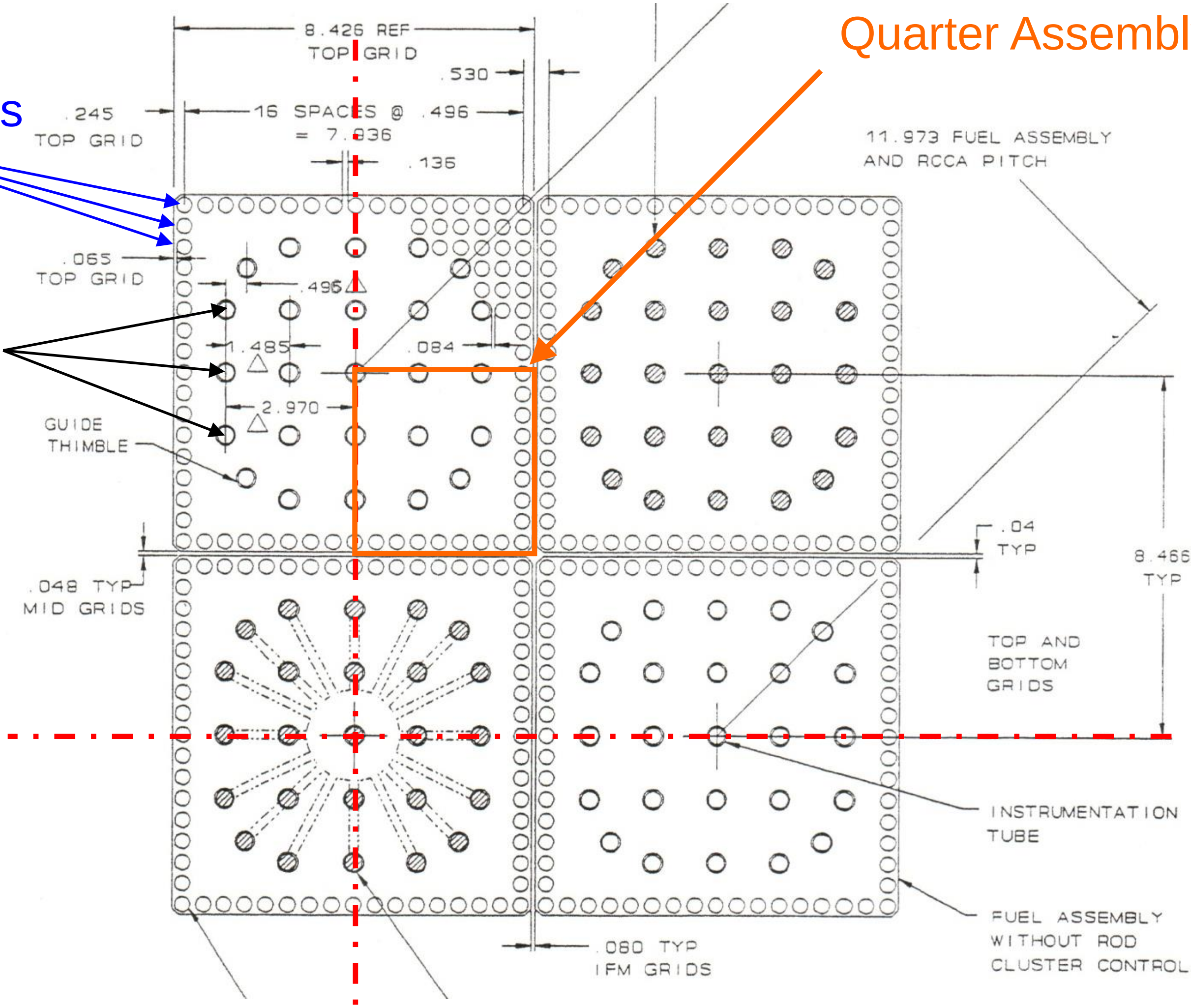
	N	M	L	K	J	H	G	F	E	D	C	B	A
1				9W	6S	10W		10W		9W			
2			9W		24W		12W 1P		24W		9W		
3		9W		24W		24W		24W		24W		9W	
4	9W		24W		24W		24W		24W		24W		9W
5		24W		24W		24W		24W		24W		24W	
6	10W		24W		24W		24W		24W		24W		10W
7		12W		24W		24W		24W		24W		12W	
8	10W		24W		24W		24W		24W		24W		10W
9		24W		24W		24W		24W		24W		24W	
10	9W		24W		24W		24W		24W		24W		9W
11		9W		24W		24W		24W		24W		9W	
12			9W		24W		12W 1P		24W		9W		
13				9W		10W		10W	6S	9W			

"Zoom In" on these 4 assemblies

Fuel Assemblies

¼ Core Symmetry

AP600 Assembly Design



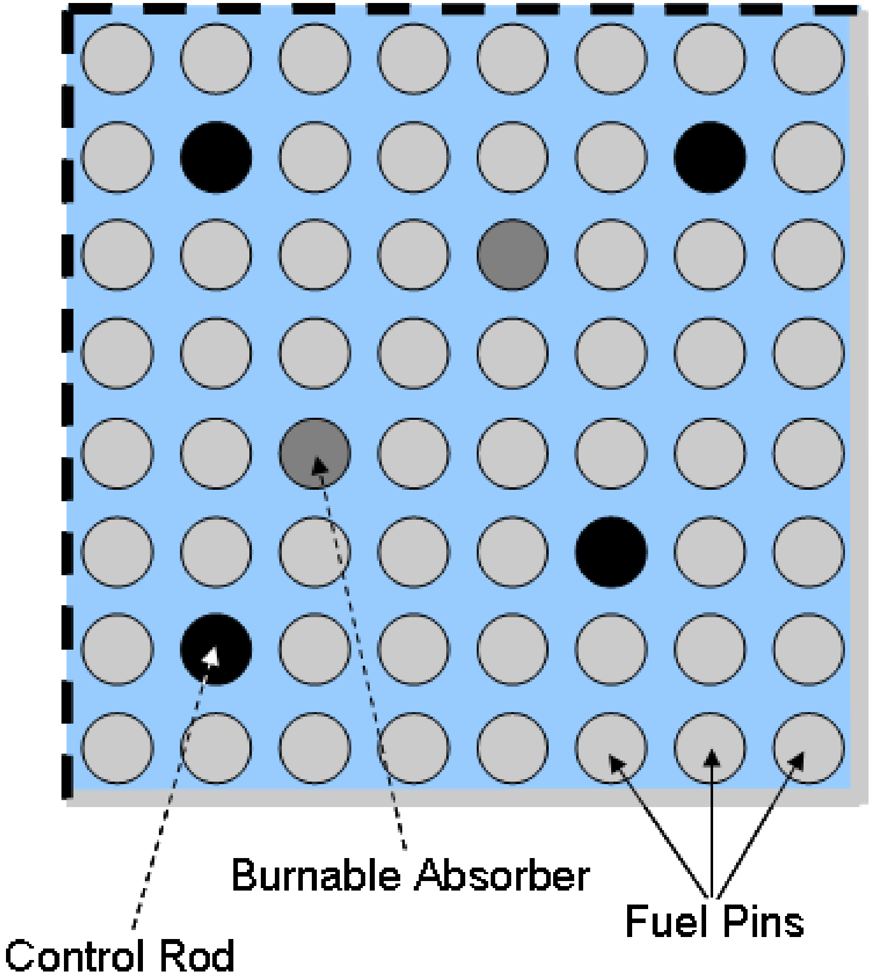
Zoom In on
Quarter Assembly

Fuel Elements

Control Rods

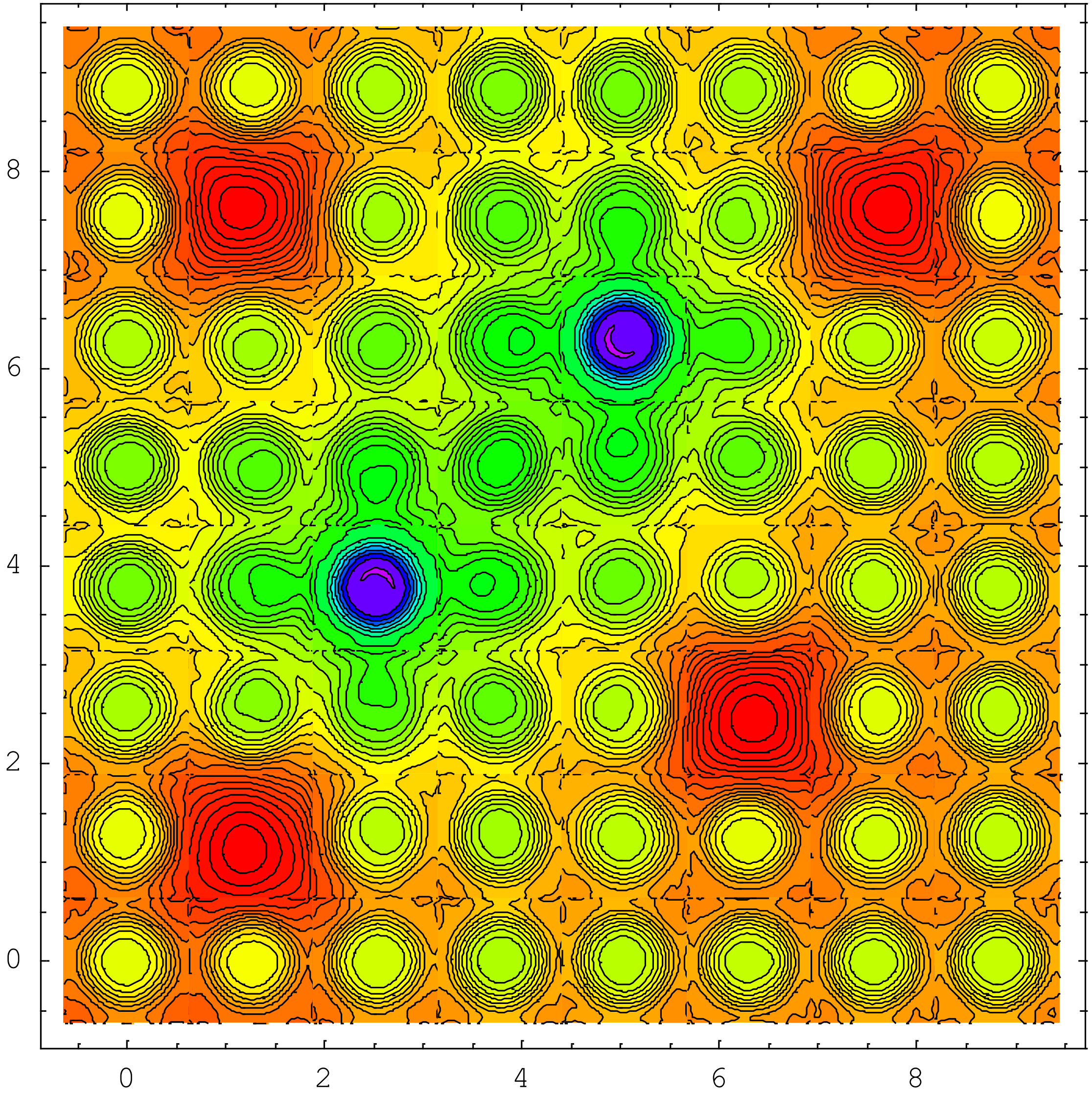
¼ Assembly
Symmetry

Simplified AP600 Assembly Model



- Simplified 2-D model of an AP600 quarter assembly.
- Contains UO2 fuel, boron control rods, and B4C burnable absorber rods.
- Reflecting boundary conditions on all sides.

Neutron Density, Control Rods Out

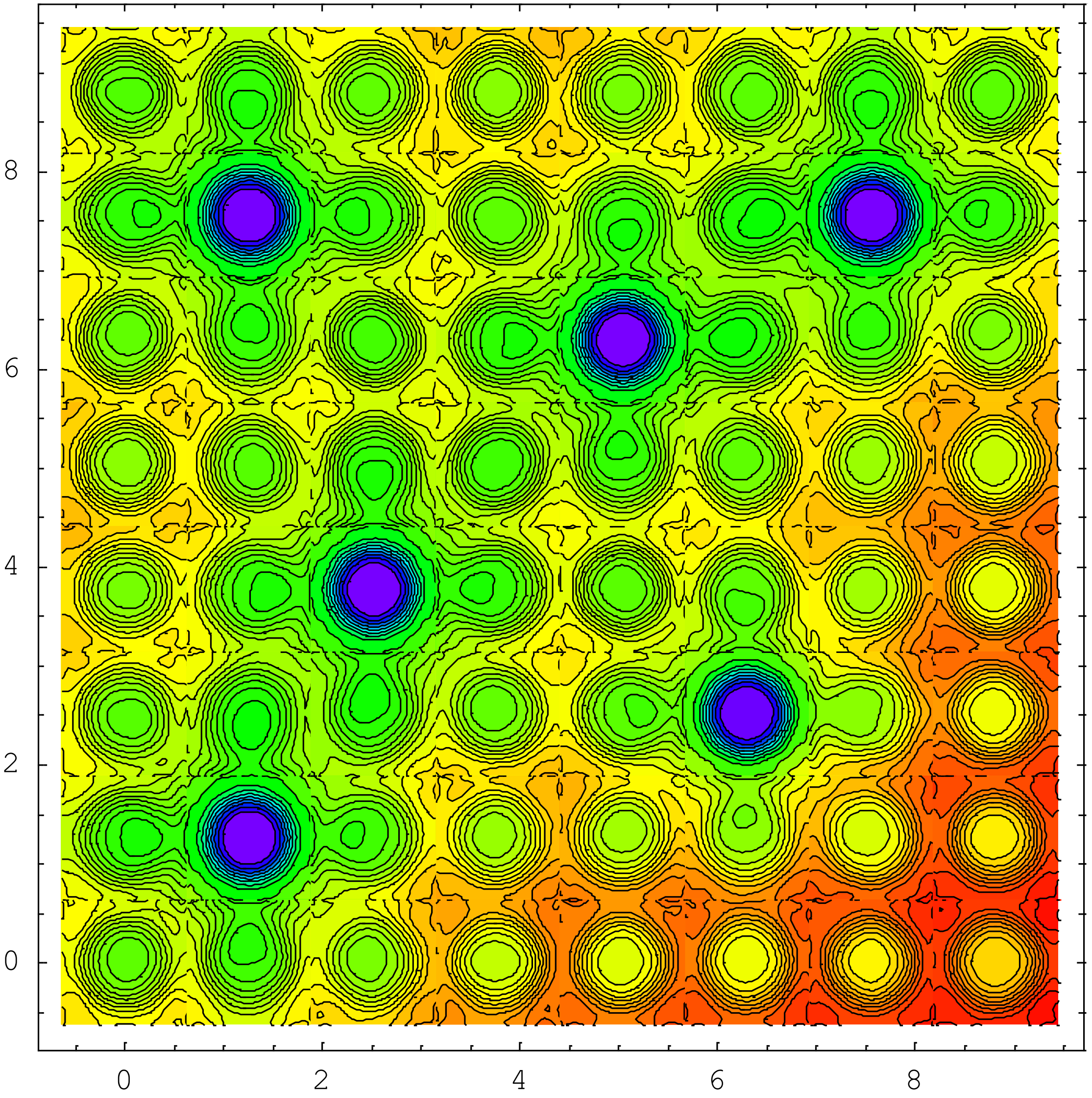


$k_{eff} = 1.1630$

- Notice the local variations in neutron density.

- Different elements can have different neutron densities.

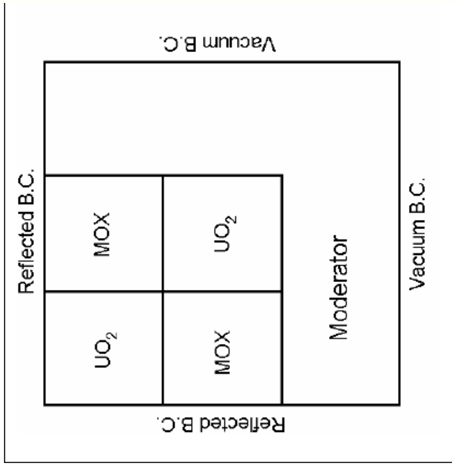
Neutron Density, Control Rods In

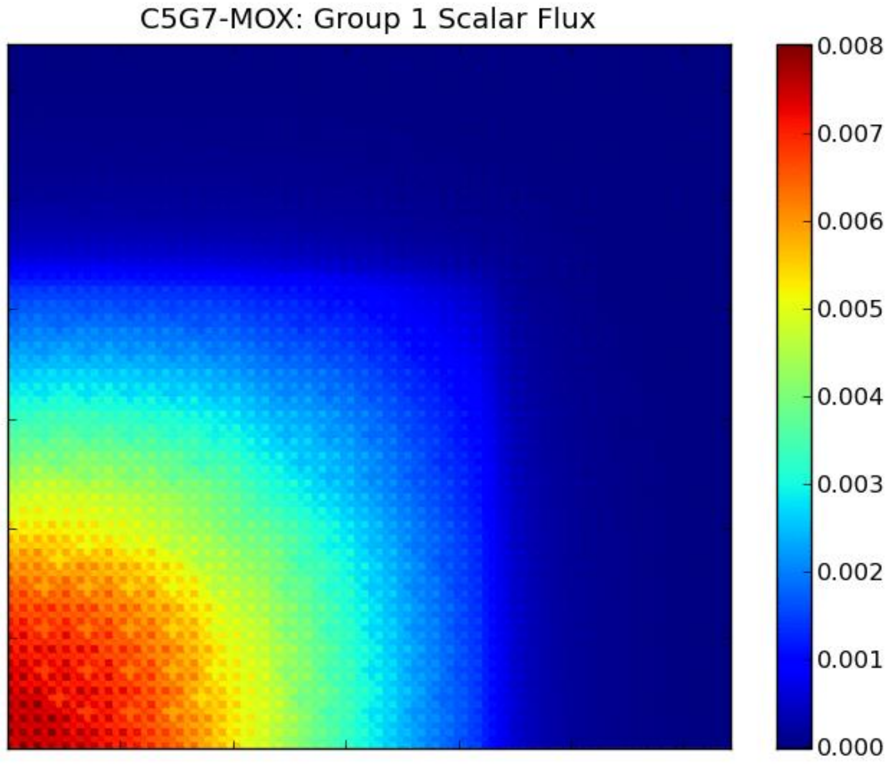


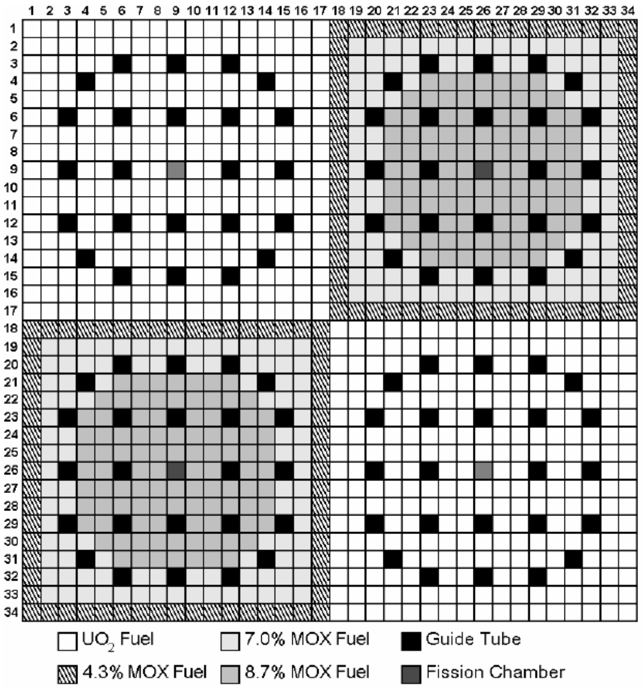
k_{eff} = 0.93287

- Notice the local variations in neutron density.
- Different elements can have different neutron densities.

Example of Energy Dependence







This is Reactor Physics

- It turns out that the nuclear and thermal behavior of the core depends on the natural distribution of neutrons in the core.
- In order to perform any type of nuclear reactor analysis we must be able to determine what the neutron distribution looks like for any given core configuration.
- How to we calculate the natural distribution of neutrons in a reactor core?
  - Not an easy task!
  - Requires us to “think” like a neutron.