22.211 Lecture 10

Reactor Design and Control

Benoit Forget

March 8, 2023

Outline

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Outline

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Objectives

- Overview of PWRs
- Overview of BWRs
- Overview of CANDUs
- Overview of VHTRs
- Overview of Fast Reactors

Light Water Reactors

- There are $\approx$450 operable commercial reactors across 31 countries.
- This represents $\approx$ 11% of the world's electricity
- $\approx$ 80% of the world's reactors are LWRs
  - Light water cooled and moderated
  - Two main types: PWR ($\approx$ 280) and BWR ($\approx$ 80)
- Alternatives
  - Gas cooled reactors (MAGNOX, AGR) ($\approx$ 15)
  - Heavy water reactors (CANDU) ($\approx$ 50)
  - Graphite moderated, water cooled (RBMK) ($\approx$ 15)
  - Sodium cooled (Joyo, Monju, Phenix, BN-600, ...) ($\approx$ 2)

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Outline

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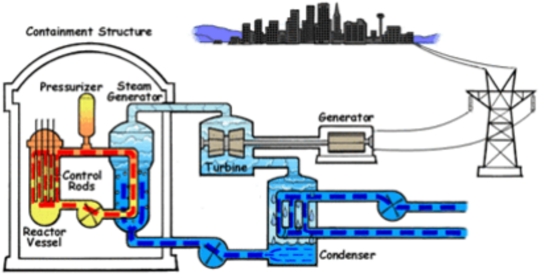
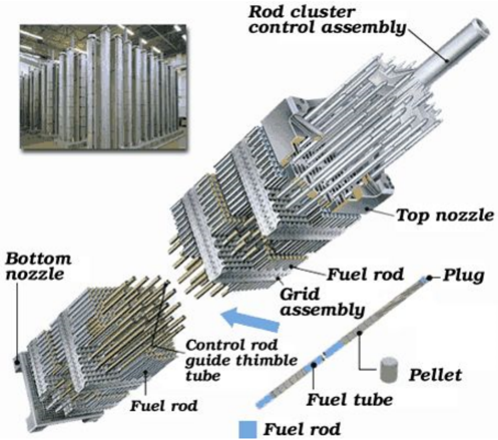
PWR

- Pressure 15 MPa
- Core inlet T $= 287°C$
- Core outlet T $= 324°C$
- ≈ 200 fuel assemblies
- 1-2 year cycles
  - Replace $\approx 1/3$ of the core
  - Fuel residence ≈ 5 years



PWR Fuel assemblies

- 21.42 cm by 21.42 cm
- Many different designs (14x14, 15x15, ... 17x17)
- Cores are designed to accept specific types
    - Difficult to change do to control rod positions and designs



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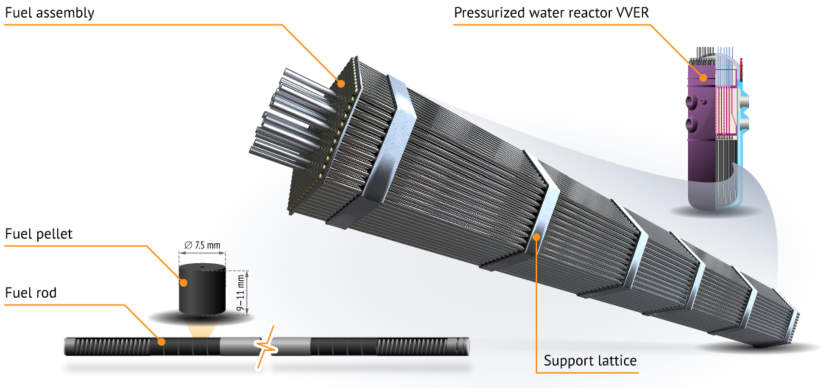
PWR Fuel assemblies



Fuel

Most common fuel type in power reactors is UO_2 (density around 10 g/cm^3)

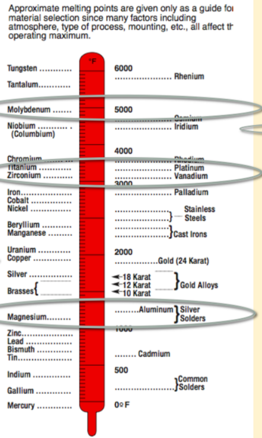
- Other fuels considered
  - Metal fuel: UZr, UZrH, UAl
  - Nitride fuel: UN (enriched nitrogen)
  - Carbide fuel: UC
  - Uranium silicide: USiAl
  - Uranium molybdenum: UMo

Why Zirconium Alloys for Rods?

Periodic Table of Elements

Sorted by Cross Section (Thermal Neutron Capture)

	Name	Sym	#
0.00019 σ_a/barns	Oxygen	O	8
0.0035 σ_a/barns	Carbon	C	6
0.007 σ_a/barns	Helium	He	2
0.0092 σ_a/barns	Beryllium	Be	4
0.0096 σ_a/barns	Fluorine	F	9
0.03 σ_a/barns	Polonium	Po	84
0.034 σ_a/barns	Bismuth	Bi	83
0.04 σ_a/barns	Neon	Ne	10
0.063 σ_a/barns	Magnesium	Mg	12
0.171 σ_a/barns	Lead	Pb	82
0.171 σ_a/barns	Silicon	Si	14
0.172 σ_a/barns	Phosphorus	P	15
0.184 σ_a/barns	Zirconium	Zr	40
0.232 σ_a/barns	Aluminum	Al	13
0.3326 σ_a/barns	Hydrogen	H	1
0.38 σ_a/barns	Rubidium	Rb	37
0.43 σ_a/barns	Calcium	Ca	20
0.53 σ_a/barns	Sulfur	S	16
0.53 σ_a/barns	Sodium	Na	11
0.6 σ_a/barns	Cerium	Ce	58
0.626 σ_a/barns	Tin	Sn	50
0.675 σ_a/barns	Argon	Ar	18
0.72 σ_a/barns	Radon	Rn	86
0.96 σ_a/barns	Platinum	Pt	78
1.11 σ_a/barns	Zinc	Zn	30
1.15 σ_a/barns	Niobium	Nb	41
1.28 σ_a/barns	Yttrium	Y	39



1.11 σ_a/barns	Zinc
1.15 σ_a/barns	Niobium
1.28 σ_a/barns	Yttrium
1.28 σ_a/barns	Strontium
1.3 σ_a/barns	Barium
1.91 σ_a/barns	Nitrogen
2.1 σ_a/barns	Potassium
2.2 σ_a/barns	Germanium
2.56 σ_a/barns	Ruthenium
2.56 σ_a/barns	Iron
2.6 σ_a/barns	Molybdenum
2.9 σ_a/barns	Gallium
3.1 σ_a/barns	Chromium
3.43 σ_a/barns	Thallium
3.78 σ_a/barns	Copper
4.3 σ_a/barns	Arsenic
4.49 σ_a/barns	Nickel
4.7 σ_a/barns	Tellurium
4.91 σ_a/barns	Antimony
5.08 σ_a/barns	Vanadium
6.09 σ_a/barns	Titanium
6.2 σ_a/barns	Iodine
6.8 σ_a/barns	Bromine
6.9 σ_a/barns	Palladium
7.37 σ_a/barns	Thorium
7.57 σ_a/barns	Uranium
8.98 σ_a/barns	Lanthanum
11.5 σ_a/barns ±0.5	Praseodymium
11.7 σ_a/barns	Selenium
12.8 σ_a/barns	Radium
13.3 σ_a/barns	Manganese

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- Static reactivity is defined as

$$\rho = \frac{k-1}{k}$$

- A change in reactivity between 2 states is defined as

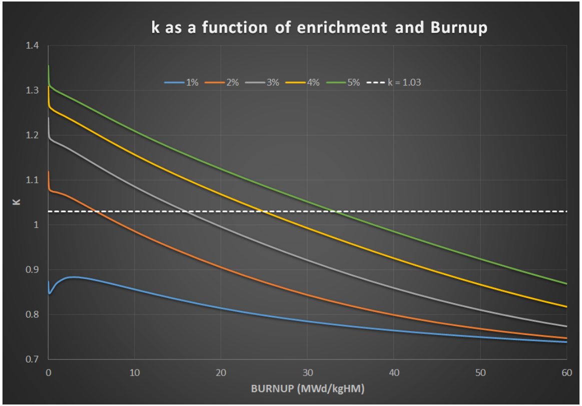
$$\rho = \frac{k_2 - k_1}{k_2 k_1}$$

- We can approximate a change in ρ to a change in k

$$d\rho = \frac{dk}{k^2} \approx \frac{dk}{k} = d(lnk)$$

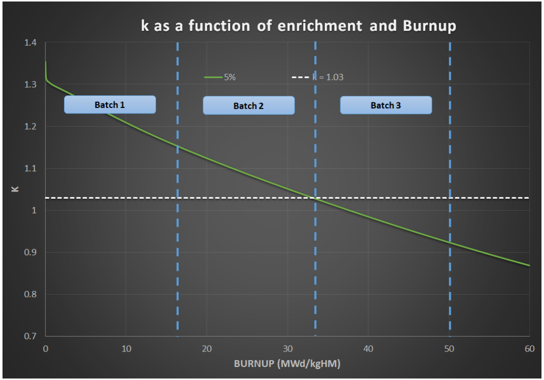
Enrichment

We can control reactivity and peak power by varying enrichment.



A typical PWR has about 3% neutron leakage, thus the infinite lattice model with $k = 1.03$ represents approximately the maximum burnup.

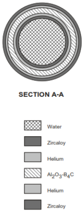
Batching is used to increase fuel utilization. In a PWR, you can achieve ≈ 1 MWd/kgHM per month and a 3 batch scheme can extend average fuel burnup by 1.5.

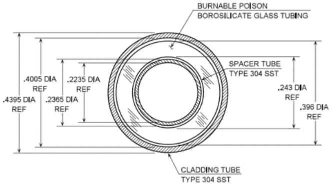


$$BU_n = \frac{2n}{n+1} BU_1$$

PWR Control Mechanisms

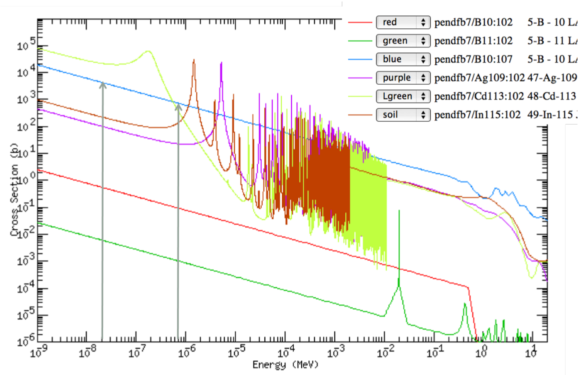
- Boron in moderator
  - Boric acid added to the water
  - pH is controlled by adding LiOH
- Control rod banks
  - Insertion from top of the core
  - B_4C or $Ag/In/Cd$
- Burnable absorbers in fuel
  - Integral: IFBA (ZrB_2 coating $< 25\ \mu m$)
  - Discrete: WABA and Borosilicate glass (Pyrex)
- Roles
  - Control excess reactivity and power distribution
  - Enable startup
  - Counteract fuel depletion, fission product absorption, negative reactivity coefficients





Control rod material

There are two main types of control rods: B4C powder and Ag/In/Cd



Depletion rate of B-10

$$\frac{dN(t)}{dt} = -N(t)\sigma_a\phi(t)$$

Assuming 2 group x.s. and constant flux

$$\frac{dN(t)}{dt} = -N(t)\sigma_{a,2}\phi_2$$

$$N(t) = N_0 e^{-\sigma_{a,2}\phi_2 t}$$

To deplete 99% of B-10

$$0.01 = 1.0e^{-\sigma_{a,2}\phi_2 t}$$

with $\sigma_{a,2} = 2000b$ and $\phi_2 = 5x10^{13} n/cm^2/s$.

Solve for t and obtain approximately 1.5 years. B-10 absorber is compatible with 18 month LWR cycle length.

Spatial shielding

B_4C pins will suffer from spatial self-shielding effects. Thermal neutrons are not likely to penetrate the center of the rod.

$$N_{B10} = (6.023x10^{23})\left(\frac{1.76}{11}\right)\left(\frac{19.8}{100}\right) = 2.0x10^{22}$$

Probability of reaching center of rod

$$P = e^{-N_{B10}\sigma_{a,2}0.386} = 2x10^{-7}$$

Boron in the rod will burn in layers. Density can be adjusted to avoid having too much residual boron at the end of the cycle.

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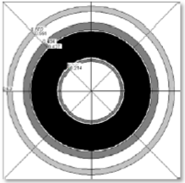
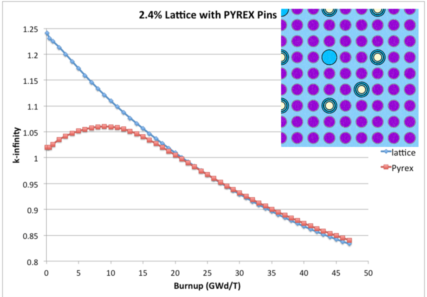
Inserted in empty control rod guide tubes

Table 6: Pyrex Rod Specification

Input	Value
Enrichment	12.5 wt% B_2O_3
Boron-10 Loading	6.24 mg/cm
Pyrex Density	2.25 g/cc
Inner Tube Inner Radius	0.214 cm
Inner Tube Outer Radius	0.231 cm
Pyrex Inner Radius	0.241 cm
Pyrex Outer Radius	0.427 cm
Cladding Inner Radius	0.437 cm
Cladding Outer Radius	0.484 cm
Poison Height	360.68 cm
Plenum Height above Poison	22.2 cm
Axial Location of Poison	15.761 cm
End Plug Height	≈ 2.54 cm
Inner Tube Material	SS304
Plenum Material	Helium
Cladding Material	SS304





$$P = e^{-N_{B10}\sigma_{a,2}0.186} = 0.0006$$

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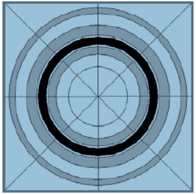
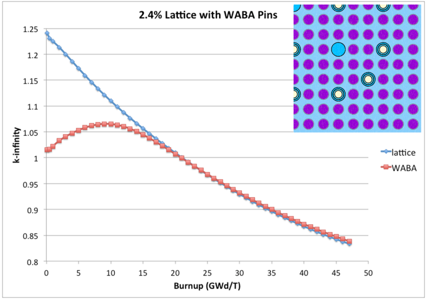
WABA pins

Inserted in empty control rod guide tubes

Table 13: WABA Rod Specification

Input	Value
Poison Material	$B_4C\text{-}Al_2O_3$
Boron-10 Loading	6.03 mg/cm
Poison Density	3.65 g/cc
Inner Clad Inner Radius	0.286 cm
Inner Clad Outer Radius	0.339 cm
Poison Inner Radius	0.353 cm
Poison Outer Radius	0.404 cm
Cladding Inner Radius	0.418 cm
Cladding Outer Radius	0.484 cm
Cladding Material	Zircaloy-4
Plenum/Gap Material	Helium





$$P = e^{-N_{B10}\sigma_{a,2}0.051} = 0.13$$

$$P = e^{-N_{B10}\sigma_{a,2}0.001} = 0.96$$

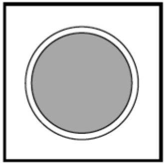
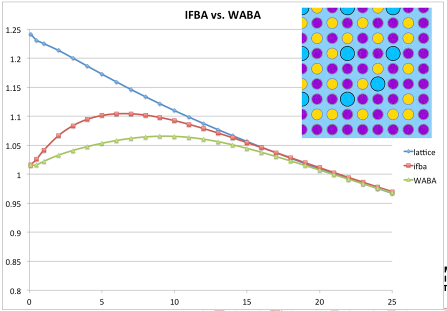


Table 1: Fuel Rod Specification (Ref. 1)

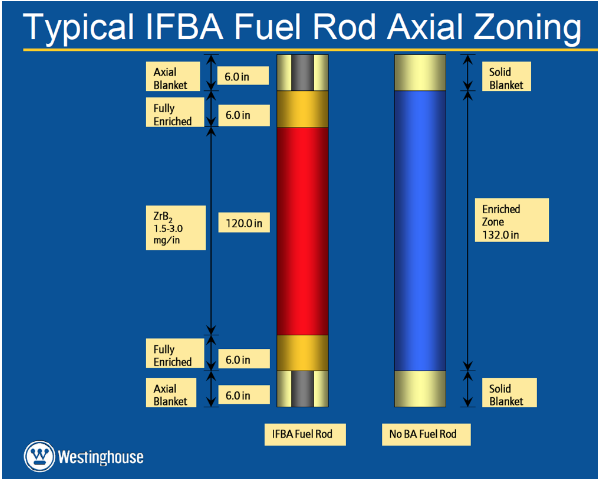
Input	Value
Pellet Radius	0.4096 cm
Inner Clad Radius	0.418 cm
Outer Clad Radius	0.475 cm
Rod Pitch	1.26 cm
Rod Height	385.1 cm
Fuel Stack Height	365.76 cm
Plenum Height	16.0 cm
End Plug Heights (x2)	1.67 cm
Pellet Material	UO_2
Clad / Caps Material	Zircaloy-4
Plenum Spring Material	Stainless Steel
Fill Gas Material	Helium

Table 11: IFBA Fuel Rod Specification

Input	Value
Poison Material	ZrB_2
Boron-10 Loading	2.355 mg/in
Boron-10 Enrichment	50%
Coating Thickness	10 μm
Coating Density	3.85 g/cc
Poison Height	304.8 cm
Poison Location	Centered axially

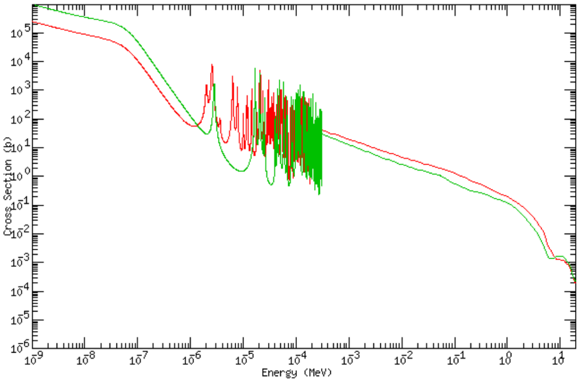


IFBA Design



Typical IFBA Fuel Rod Axial Zoning
Axial Blanket
6.0 in
Fully Enriched
6.0 in
ZrB2 1.5-3.0 mg/in
120.0 in
Fully Enriched
6.0 in
Axial Blanket
6.0 in
Solid Blanket
Enriched Zone 132.0 in
Solid Blanket
IFBA Fuel Rod
No BA Fuel Rod
Westinghouse

Gd



Gd-155 (14.80%) in red, Gd-157 (15.65 %) in green.

Gd Depletion rate

$$\frac{dN(t)}{dt} = -N(t)\sigma_a\phi(t)$$

Assuming 2 group x.s. and constant flux

$$\frac{dN(t)}{dt} = -N(t)\sigma_{a,2}\phi_2$$

$$N(t) = N_0 e^{-\sigma_{a,2}\phi_2 t}$$

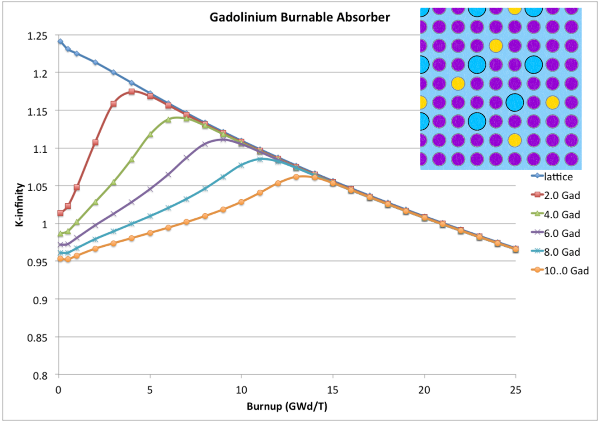
To deplete 99% of Gd-155

$$0.01 = 1.0e^{-\sigma_{a,2}\phi_2 t}$$

with $\sigma_{a,2} = 20,000b$ and $\phi_2 = 5x10^{13} n/cm^2/s$.

Solve for t and obtain approximately 0.15 years. Gd-155 burns very fast, thus needing spatial self-shielding to extend its life.

Gd Depletion



Gd is mixed with the fuel as an oxide powder. Burnout rate varies with concentration.

Outline

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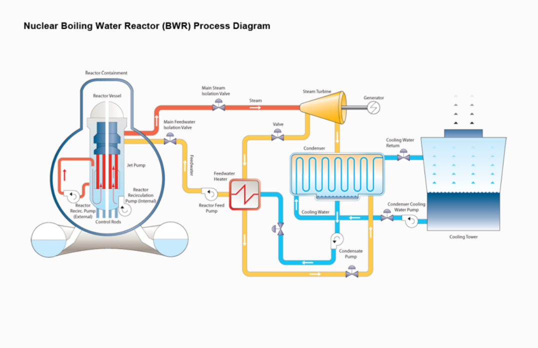
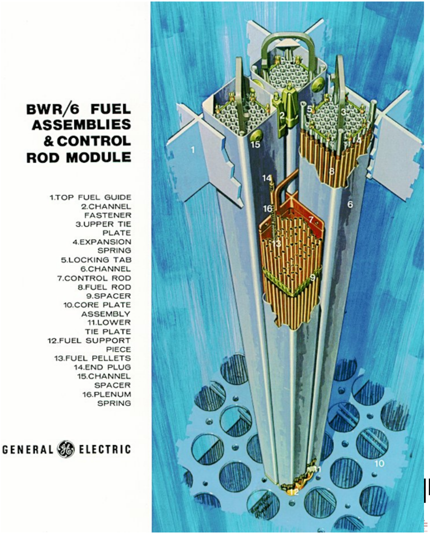
BWR

- Pressure 7.6 MPa
- Core inlet T = 278°C
- Core outlet T = 287°C
- ≈ 800 fuel assemblies
- 1-2 year cycles
    - Replace ≈ 1/3 of the core
    - Fuel residence ≈ 5 years

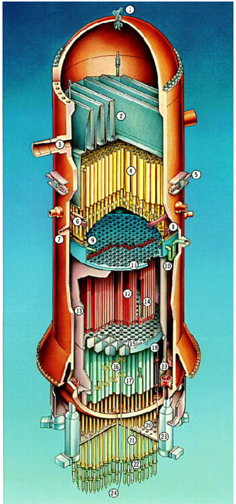


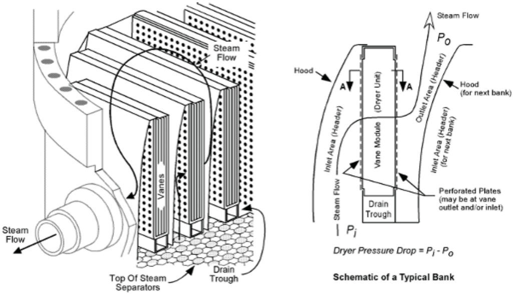
BWR Fuel assemblies

- 15.24 cm by 15.24 cm
- More design variations then PWR
    - Water holes
    - Part length rods
    - Gray rods



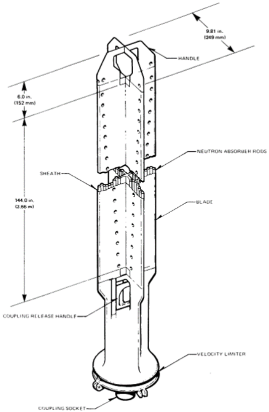
BWR Steam Separators and Dryers





BWR Control Mechanisms

- Cruciform control blades
  - Driven from the bottom of the core
  - Boron carbide powder
- Burnable absorbers in fuel
  - Gadolinium bearing pins
- Coolant feed flow



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Outline

Reactivity Coefficients

We commonly define reactivity coefficients as

$$\alpha_x = \frac{1}{k}\frac{\partial k}{\partial x}$$

Static calculations are performed to evaluate reactivity changes with respect to

- fuel temperature
- moderator/coolant temperature/density
- geometrical changes
- ...

Fuel temperature coefficient

Doppler broadening of the resonances increases absorption in the slowing down process

- Resonances become wider
- Flux depression becomes wider
- Less neutrons reach thermal energies, thus fission rate goes down
- Dominated by U-238 resonance absorption in LWRs
- Reactivity coefficient is approximately -3 pcm/K

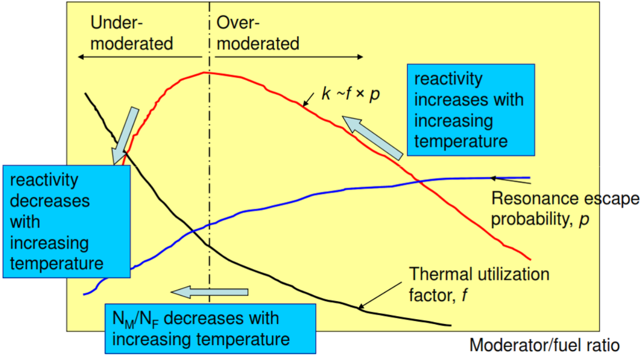
Moderator temperature coefficient

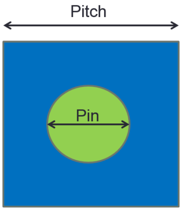
An increase in moderator temperature will have an impact on reactivity

- Temperature in the water increases
- Density is reduced
- Macroscopic cross section is reduced
- Less moderation (harder spectrum)

PWRs and BWRs were designed to have negative temperature coefficients under normal operating conditions. Boron concentration will also impact the moderator temperature coefficient.

Moderator temperature coefficient





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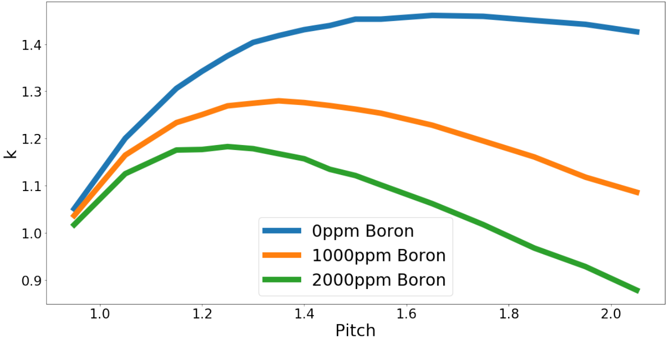
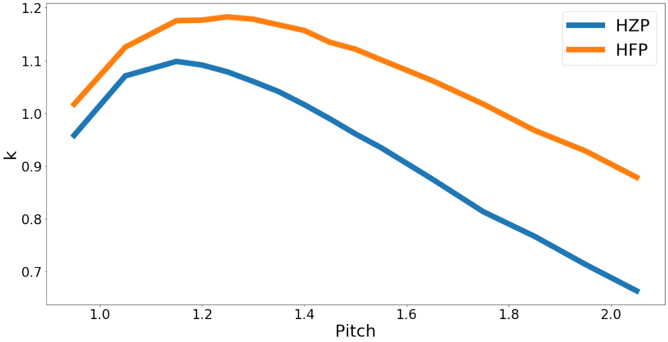
Boron in moderator



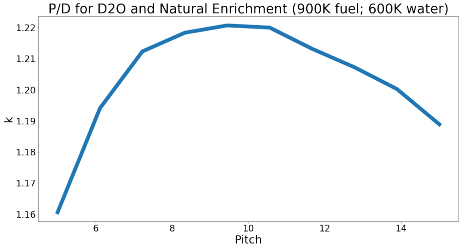
Temperature effect (with 2000ppm Boron)

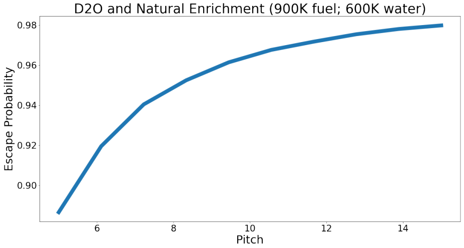


Temperature also effects optimal pitch to diameter ratio and can change the sign of the reactivity coefficient.

Outline

Heavy Water

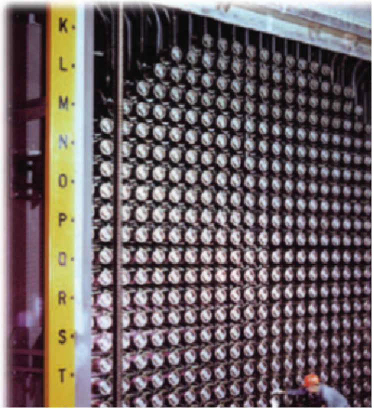




Another major difference between LWRs and HWRs is the prompt neutron lifetime. Implications can be seen in reactor control, the longer the neutrons lives, the longer it takes for power to increase (or decrease)

- HWRs have a prompt neutron lifetime 2 orders of magnitude larger!

The CANDU Reactor

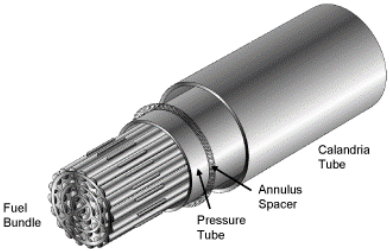


CANDU-6

- 380 channels
- 7m diameter
- 6m active core
- 2200 MWth
- 650 MWe
- 10 MPa
- 310C

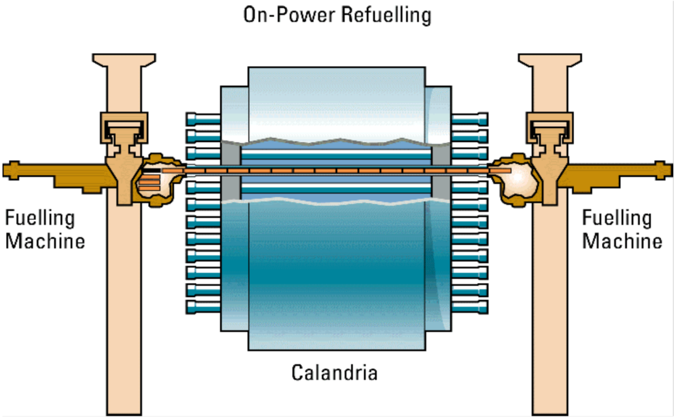
Pressure Tube

- Very large and thick pressure vessel would have been required
- Pressure tubes can be much thinner
  - PT 4mm
  - CT 1.5mm

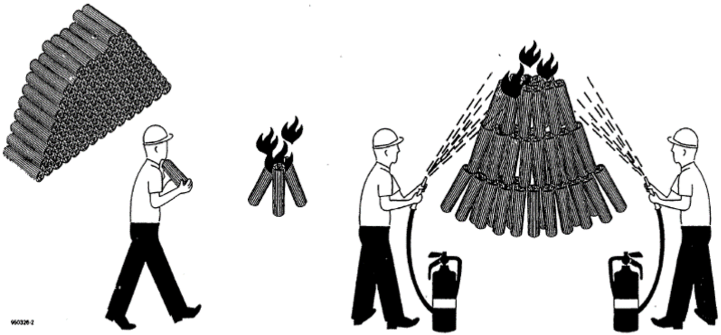


CANDU Online Refuelling

Fueling machines at both ends of the reactor to insert and remove irradiated fuel.



Refuelling and Excess Reactivity



CANDU
Fuel added as needed

LWR
18 months fuel added at once.
Burning rate suppressed.

Control Mechanisms

- Boric acid is only used at startup of a new plant
- Reactivity is controlled by
  - Control rods in 21 sectors for core balancing
  - Liquid zone controllers
    - Light water is a poison in a heavy water system
  - Online fuel loading is performed to flattened power and maitain reactivity
    - 1 channel per day (8 bundles replaced)
  - No need for burnable absorbers since excess reactivity is quite low
    - Dysprosium has been used in some reactors to help reduce postive void coefficients

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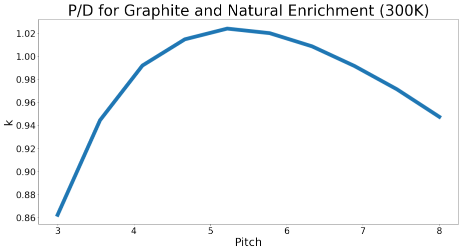
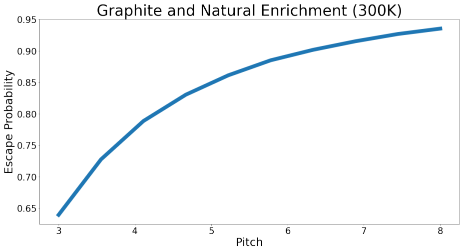
Outline

1. Objectives
2. PWR
3. BWR
4. Reactivity Coefficients
5. Heavy water
6. Graphite
7. Fast Reactors
8. Other Reactivity Control Mechanisms

Graphite





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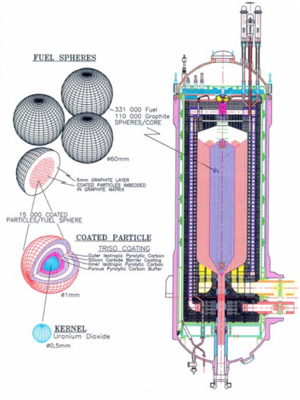
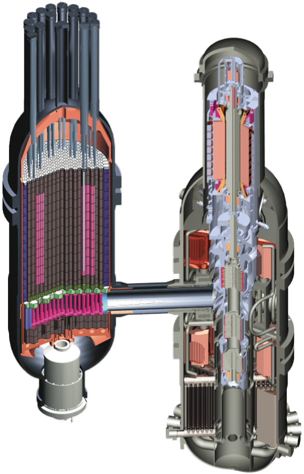
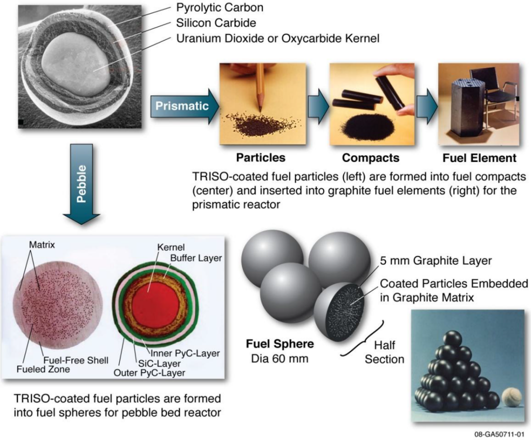
Types of VHTR





VHTR Fuel


Pyrolytic Carbon
Silicon Carbide
Uranium Dioxide or Oxycarbide Kernel
Prismatic
Particles
Compacts
Fuel Element
TRISO-coated fuel particles (left) are formed into fuel compacts (center) and inserted into graphite fuel elements (right) for the prismatic reactor
Pebble
Matrix
Kernel
Buffer Layer
Inner PyC-Layer
SiC-Layer
Outer PyC-Layer
Fuel-Free Shell
Fueled Zone
TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor
5 mm Graphite Layer
Coated Particles Embedded in Graphite Matrix
Fuel Sphere
Dia 60 mm
Half Section
08-GA50711-01

Advantages

Light water

- Affordable
- Compact
- Negative void coefficients

Heavy water

- Neutron economy
- Large neutron lifetime

Graphite

- Neutron economy
- Large neutron lifetime
- Reasonable cost

Disadvantages

Light water

- High enrichment
- Small neutron lifetime

Heavy water

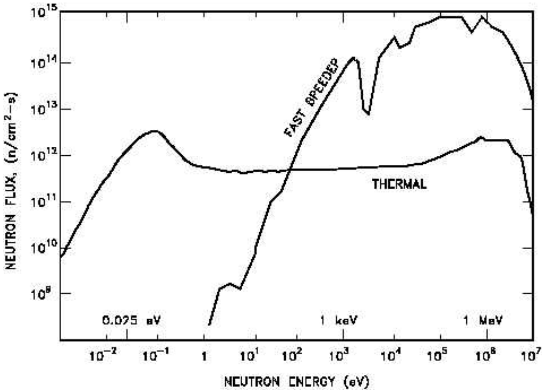
- High cost
- Low power density

Graphite

- Impurities
- Low power density

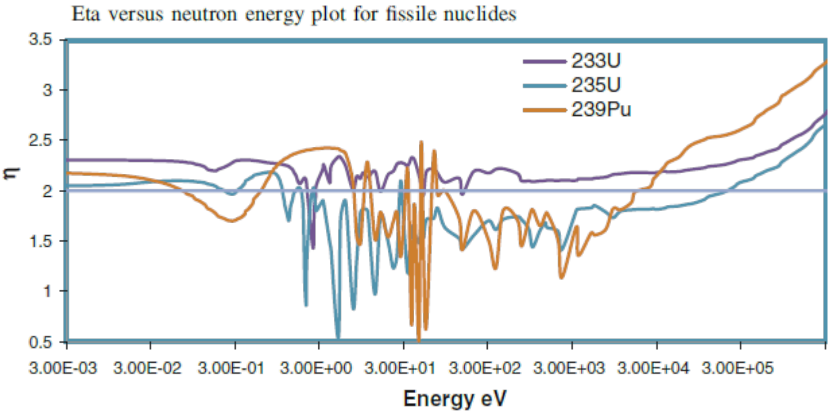
Outline

Spectrum



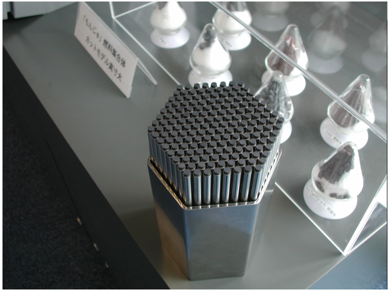
NEUTRON FLUX, (n/cm^2−s)
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
FAST SPEEDER
THERMAL
0.025 eV
1 keV
1 MeV
10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
NEUTRON ENERGY (eV)

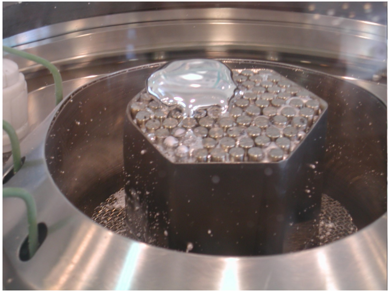
Why fast reactors?



Source: Aqueous Reprocessing by THOREX Process, 2013, by P. V. Achuthan & A. Ramanujam, page 281

Fuel Assemblies





Outline

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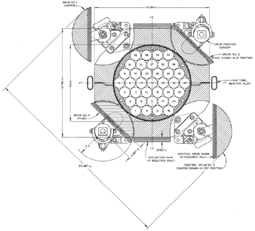
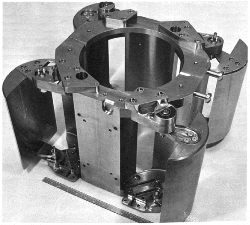
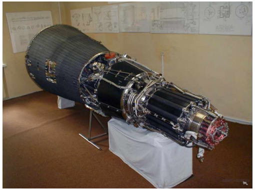
Rotating reflector





Rotating control drums



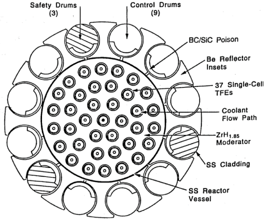
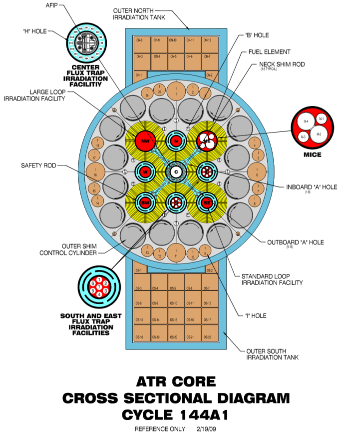
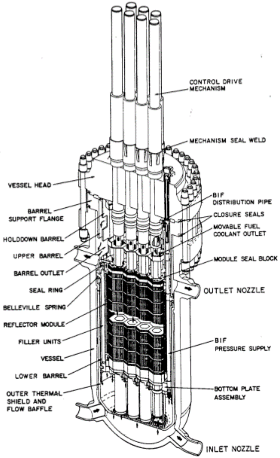
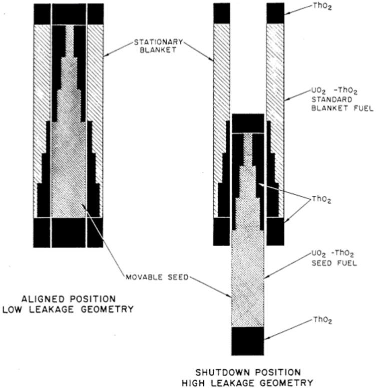


Figure 2. Top View of the TOPAZ II Reactor.



Movable fuel





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