
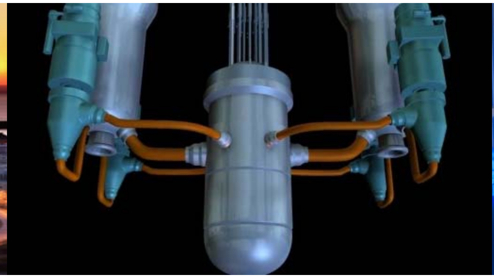
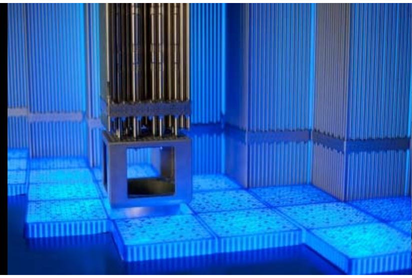


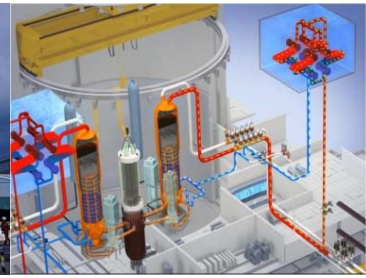

NUCLEAR SYSTEMS ENGINEERING

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Contents of Lecture

- Contents of lecture
  - Chapter 1 Principal Characteristics of Power Reactors
    - Will be replaced by the lecture note
    - Introduction to Nuclear Systems

Nuclear system

  - Chapter 4 Transport Equations for Single-Phase Flow (up to energy equation)
  - Chapter 6 Thermodynamics of Nuclear Energy Conversion Systems: Nonflow and Steady Flow : First- and Second-Law Applications
  - Chapter 7 Thermodynamics of Nuclear Energy Conversion Systems : Nonsteady Flow First Law Analysis

Thermodynamics

  - Chapter 3 Reactor Energy Distribution
  - Chapter 8 Thermal Analysis of Fuel Elements

Heat transport
Conduction
heat transfer

3. REACTOR ENERGY DISTRIBUTION

Contents

Introduction

- Energy Generation Distribution throughout the Nuclear Reactor
  - Neutronic analysis of the reactor
  - Not covered in the present course

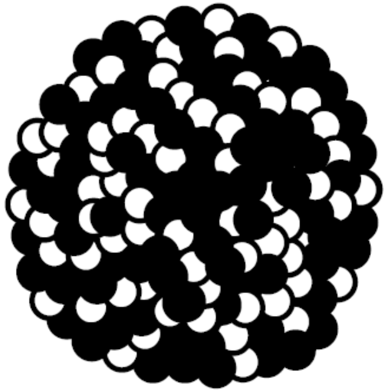
- Limitation of the operational power of the core
  - Limited by thermal consideration
    - Heat that can be transported from fuel to coolant
  - Consequence of the violation of the limit
    - Excessively high temperature $\Rightarrow$ degradation of the fuel and structures
    - Cracking at low temperatures

- This chapter covers
  - Fission energy generation and deposition during reactor operation
  - Shutdown energy generation
    - Decay power after reactor shutdown
  - Sources of energy generation from the chemical reactions
    - In accident scenarios

Energy Generation And Deposition

- Fission process
  - Naturally occurring Uranium

$^{234}_{92}U$	$^{235}_{92}U$	$^{238}_{92}U$
92 Protons 142 Neutrons	92 Protons 143 Neutrons	92 Protons 146 Neutrons
Far less than 1 %	0.7 %	99.3 %



$_{92}U$

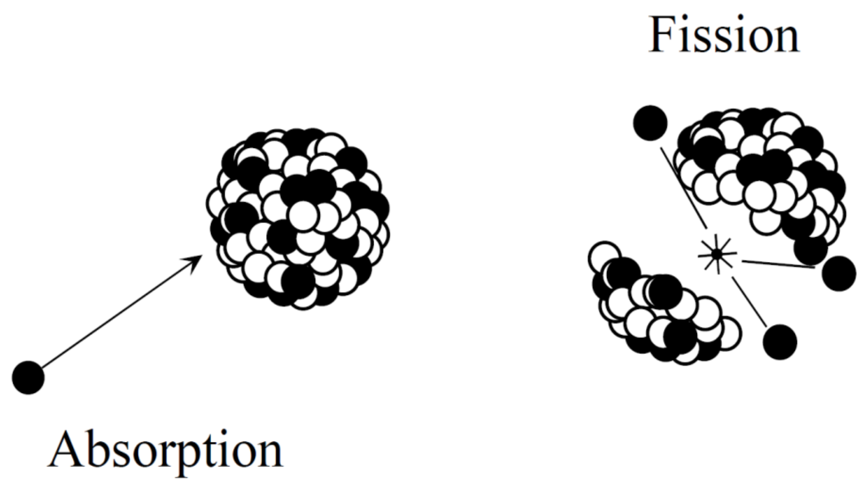
  - Enrichment

Uranium Ore (0.7%)

Fuel Pellet (3.5%)

Energy Generation And Deposition

- Fission process
  - Uranium-235
    - Useful as a reactor fuel because:
    - It will readily absorb a neutron to become the highly unstable isotope U-236.
    - U-236 has a high probability of fission (about 80% of all U-236 atoms will fission).
    - The fission of U-236 releases energy (in the form of heat)
    - The fission of U-236 releases two or three additional neutrons which can be used to cause other fissions, and establish a "chain reaction."



Energy Generation And Deposition

- Energy generated in a reactor
  - Fission
  - Non-fission neutron capture
    - Fuel, moderator, coolant and structure materials
  - Fissile and fertile atoms
    - Fissile: one prone to fission on absorption of a neutron of any energy
      - Uranium 235
      - Other fissile materials: generated by neutron capture in the fertile atoms
    - Fertile atoms
      - Uranium 238 $\Rightarrow$ plutonium 239
      - Plutonium 240 $\Rightarrow$ plutonium 241
      - Thorium 232 $\Rightarrow$ uranium 233

Energy Generation And Deposition

- Energy generated in a reactor
  - Energy release on fission (Unik and Gindler)

$$E_f(\text{MeV/fission}) = 1.29927 \times 10^{-3}(Z^2 A^{0.5}) + 33.12$$

⟸ Error in the textbook!

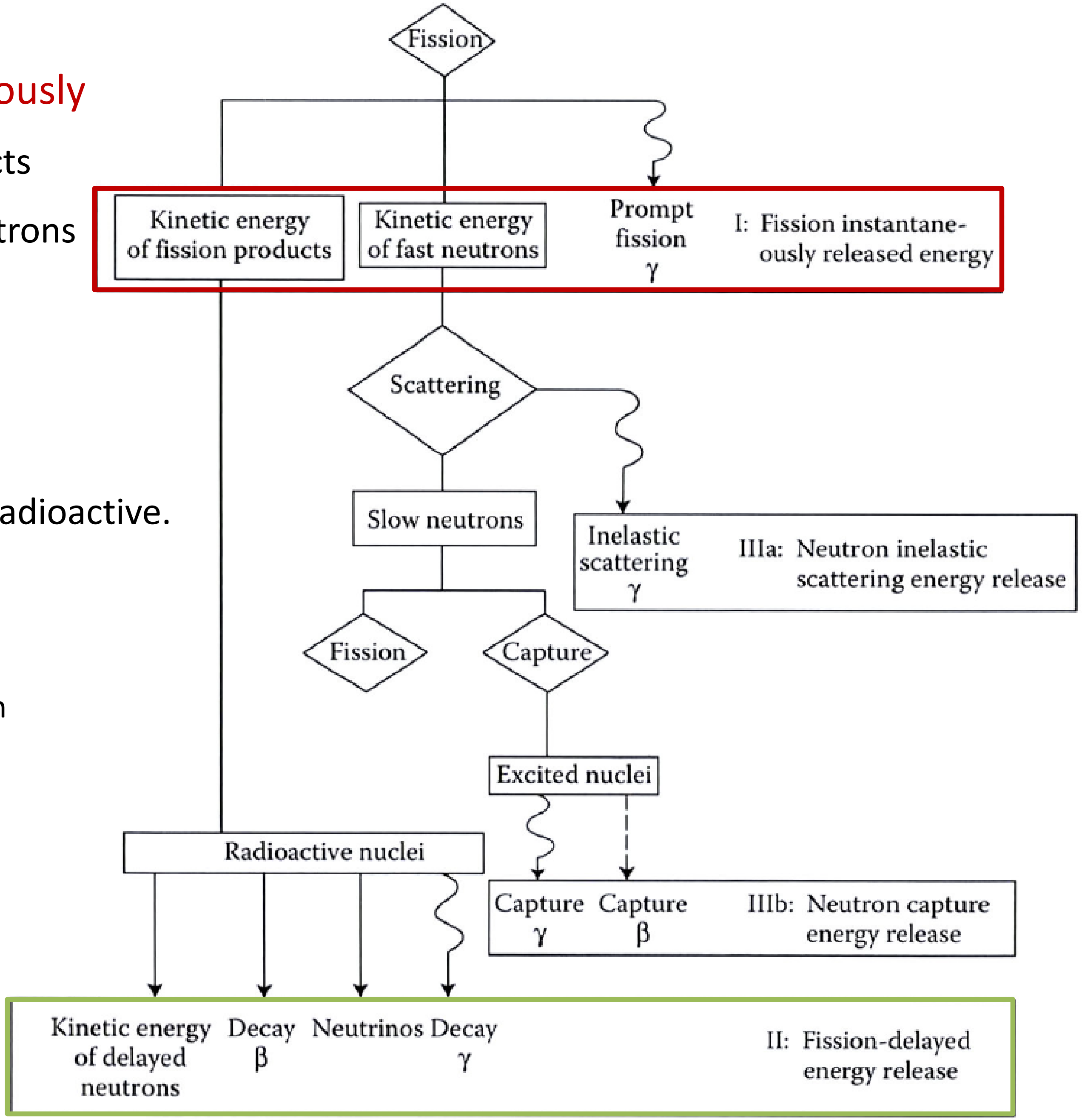
    - Z: atomic number (for example, 92)
    - A: atomic mass (for example, 235)
    - Roughly, 200 MeV = 3.2×10^{-11} J per fission

eV = 1.6×10^{-19} J

  - In a typical LWR
    - One-half of the neutrons: absorbed in fissile isotopes
    - One-half of the neutrons: absorbed in fertile isotopes, control rod, and structural materials
      - Plutonium is produced.
      - Up to 50 % of fission energy release near the end of a fuel cycle

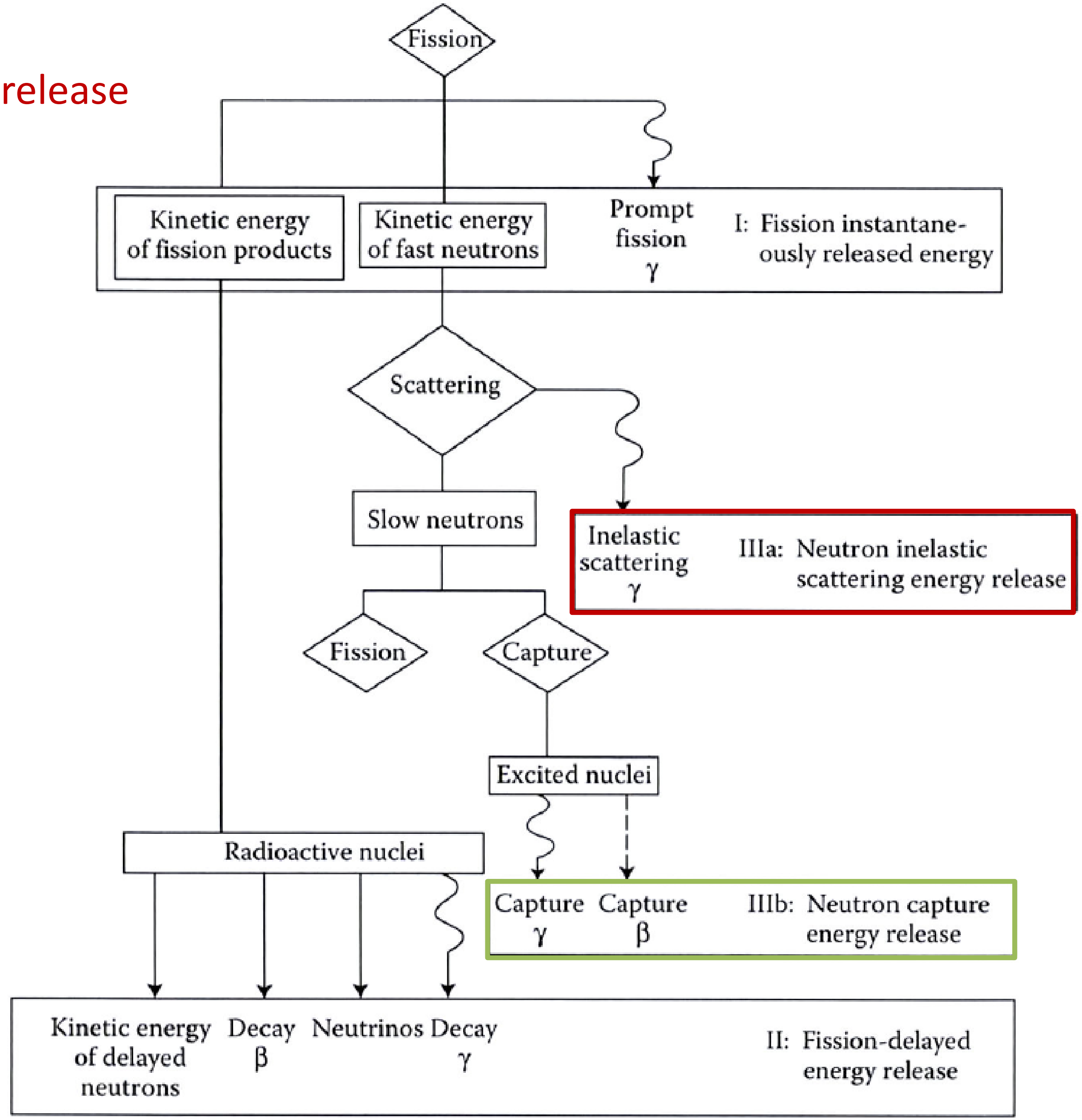
Energy Generation And Deposition

- Energy generated in a reactor
  - Fission energy: released instantaneously
    - Kinetic energy of the fission products
    - Kinetic energy of the newborn neutrons
    - Energy of γ-rays
    - Energy of neutrinos
  - Fission-delayed energy release
    - Many of the fission fragments are radioactive.
    - β-decay $\Rightarrow$ neutron release
      - Makes certain isotopes unstable
      - Delayed neutrons + γ-ray emission



Energy Generation And Deposition

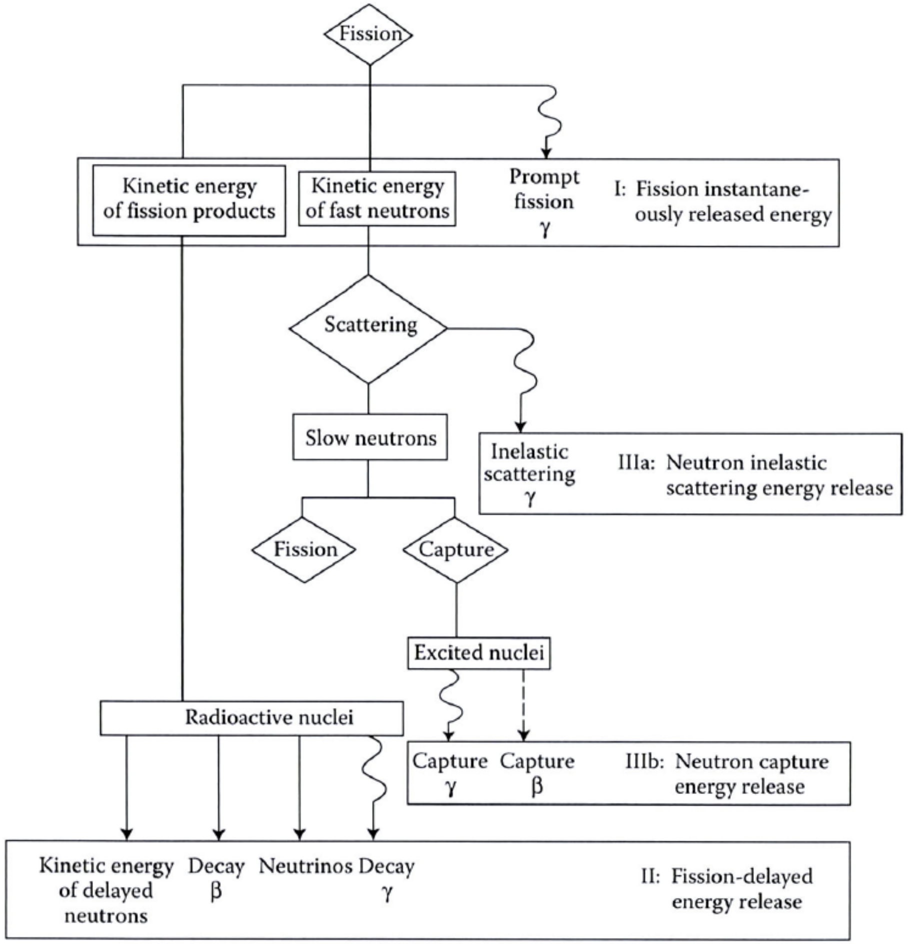
- Energy generated in a reactor
  - Neutron inelastic scattering energy release
    - Fast neutrons: 1~2 MeV
    - Neutron moderation
      - Potential for being absorbed is improved.
      - Thermal neutron (< 1 eV)
      - The most energy loss per collision occurs with light nuclei atoms
      - The best moderating material
        ⇒ those with low atomic masses
        ⇒ Carbon, hydrogen, deuterium
  - Neutron capture energy release
    - Excited nuclei emits β- and γ-rays



Energy Generation And Deposition

- Energy generated in a reactor

Type	Process	Percent of Total Released Energy	Principal Position of Energy Deposition
	Fission		
I. Instantaneously released energy	Kinetic energy of fission products	80.5	Fuel
	Kinetic energy of newly born fast neutrons	2.5	Moderator
	γ-Energy released at time of fission	2.5 (1.3/1.2)	Fuel/structures
II. Delayed energy	β-Decay energy of fission products	3.0	Fuel
	Neutrinos associated with β-decay	5.0	Nonrecoverable
	γ-Decay energy of fission products	3.0 (1.6/1.4)	Fuel/structures
	Kinetic energy of delayed neutrons	0.02	Moderator
Subtotal fission		96.5	
	Inelastic Scattering and Neutron Capture		
III. Instantaneously released and delayed energy	Nonfission reactions due to excess neutrons plus β- and γ-decay energy of (n, γ) products	3.5 (2.0/1.5)	Fuel and structures
Total		100	



Energy Generation And Deposition

- Energy deposition
  - Previous part: energy generation
  - Fission products
    - Kinetic energy of the fission products: ~ 80% of total heat generation
    - Deposited in a short range: < 0.25 mm
  - γ- and β-rays
    - Released in in structural as well as fuel materials
  - Neutrons
    - Considerable amount of their kinetic energy is released in the moderator and the structure.
  - Neutrino energy
    - Unrecoverable $\Rightarrow$ do not interact with the surrounding materials

Energy Generation And Deposition

- Energy deposition
  - For a LWR,
    - 88.4% of the total energy released per fission recovered in fuel
    - 2.5% in moderator
    - 4.1 % in the structure
    - 5 % unrecoverable (neutrino energy)

Contents

Fission Power And Calorimetric (Core Thermal) Power

- Fission power and core thermal power
  - $\dot{Q}_f$: total energy generated in the core due to fission
    - Includes all the various forms of energy release
      - Fission, inelastic scattering, neutron capture
    - 5% is carried away by neutrinos
  - The amount of energy deposited in the core
    - $\dot{Q}_{th} = 0.95\dot{Q}_f$ Core thermal power

$$\dot{Q}_{\text{th}} = \sum_{n=1}^{N} \dot{q}_n + \dot{Q}_{\text{moderator and noncladding structure}}$$

- $\dot{q}_n$: average energy deposition in a fuel rod
- N_p: number of fuel rods (pins) in the core

- $\dot{Q}_{fuel} = 0.884\dot{Q}_f$
- $\dot{Q}_{cladding} = 0.03\dot{Q}_f$

$$= \sum_{n=1}^{N} \dot{q}_n$$

Process	Percent of Total Released Energy	Principal Position of Energy Deposition
Fission		
Kinetic energy of fission products	80.5	Fuel
Kinetic energy of newly born fast neutrons	2.5	Moderator
γ-Energy released at time of fission	2.5 (1.3/1.2)	Fuel/structures
β-Decay energy of fission products	3.0	Fuel
Neutrinos associated with β-decay	5.0	Nonrecoverable
γ-Decay energy of fission products	3.0 (1.6/1.4)	Fuel/structures
Kinetic energy of delayed neutrons	0.02	Moderator
	96.5	
Inelastic Scattering and Neutron Capture		
Nonfission reactions due to excess neutrons plus β- and γ-decay energy of (n, γ) products	3.5 (2.0/1.5)	Fuel and structures
	100	

Fission Power And Calorimetric (Core Thermal) Power

- Fission power and core thermal power
  - Core thermal power deposited in the fuel rod

$$0.914\dot{Q}_{\mathrm{f}} = 0.914\left(\frac{\dot{Q}_{\mathrm{th}}}{0.95}\right) = 0.962\dot{Q}_{\mathrm{th}} \qquad \because \quad \dot{Q}_{\mathrm{th}} = 0.95\dot{Q}_{\mathrm{f}}$$

$$\dot{Q}_{\mathrm{th}} = \frac{1}{0.962}\sum_{n=1}^{N_{\mathrm{p}}}\dot{q}_n \equiv \frac{1}{\gamma}\sum_{n=1}^{N_{\mathrm{p}}}\dot{q}_n \qquad \because \quad 0.914\dot{Q}_{\mathrm{f}} = \sum_{n=1}^{N}\dot{q}_n$$

    - γ: fraction of the core thermal power deposited in the fuel rods

$$\gamma\dot{Q}_{\mathrm{th}} = \sum_{n=1}^{N}\dot{q}_n \quad \Longrightarrow \quad \dot{Q}_{\mathrm{th}} = \sum_{n=1}^{N}\dot{q}_n + \dot{Q}_{\text{moderator and noncladding structure}}$$

$$\frac{\dot{Q}_{\text{moderator and non-cladding structure}}}{\dot{Q}_{\mathrm{th}}} = 1-\gamma$$

    - $1-\gamma$: fraction of the core thermal power deposited in the moderator and non-cladding structure

Fission Power And Calorimetric (Core Thermal) Power

- Fission power and core thermal power
  - Power definitions and typical PWR conditions

Fission Power		**Calorimetric Core Power**	
Fission energy, $\dot{Q}_f$: $\frac{3411}{0.95} = 3591\,\text{MW}_{\text{th}}$		Core thermal power, $\dot{Q}_{\text{th}}$: 3411 MW_{th}	
% Deposition in		% Deposition in	
Fuel rods	91.4%	Fuel rods	96.2%[b] (91.4%/0.95)
Moderator	2.5%	Moderator	2.6%
Noncladding structure	1.1%	Noncladding structure	1.2%
Neutrinos	5%	Neutrinos	—

Fission Power

Core average volumetric energy generation rate

$$\langle q_f''' \rangle = \frac{\dot{Q}_f}{V_{\text{core}}} = \frac{3591}{32.63} = 110\frac{\text{MW}}{\text{m}^3}$$

Calorimetric Core Power

Core average volumetric energy generation rate in the fuel

$$\langle q''' \rangle \equiv \frac{\gamma \dot{Q}_{\text{th}}/N_p}{V_f} = \frac{(0.962)3411/50952}{1.93\times 10^{-4}} = 334\,\text{MW/m}^3$$

Core average volumetric energy generation rate (the power density)

$$\langle q''' \rangle_{\text{core}} \equiv \frac{\dot{Q}_{\text{th}}}{V_{\text{core}}} = \frac{3411}{32.63} = 104.5\frac{\text{MW}}{\text{m}^3}$$