University of Pittsburgh

ME/ENGR 2100 Fundamentals of Nuclear Engineering

Radiation and Nuclear Reactions:

Nuclear Fission

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Relevant Reading Assignments

- Chapter 2/3 of "Introduction to Nuclear Engineering," Lamarsh and Baratta, 3rd edition, Prentice-Hall (2001)
- Chapter 2 of "Nuclear Engineering: Theory and Technology of Commercial Nuclear Power," Knief, 2nd edition, American Nuclear Society (1992, reprint by ANS 2008)
- Chapter 2 of "Nuclear Reactor Analysis," Duderstadt and Hamilton, Van Nostrand (1976)
- Module 1 of DOE Fundamentals Handbook, "Nuclear Physics and Reactor Theory," U.S.DOE (1993)Available at:

https://www.standards.doe.gov/standards-documents/1000/1019-bhdbk-1993-v1

- Not required but useful and clear is the discussion of nuclear masses and binding energies at the beginning of Chapter 7 of "Concepts of Nuclear Physics" by Bernard L. Cohen, McGraw-Hill, 1971, available in most scientific libraries.

Learning Objectives

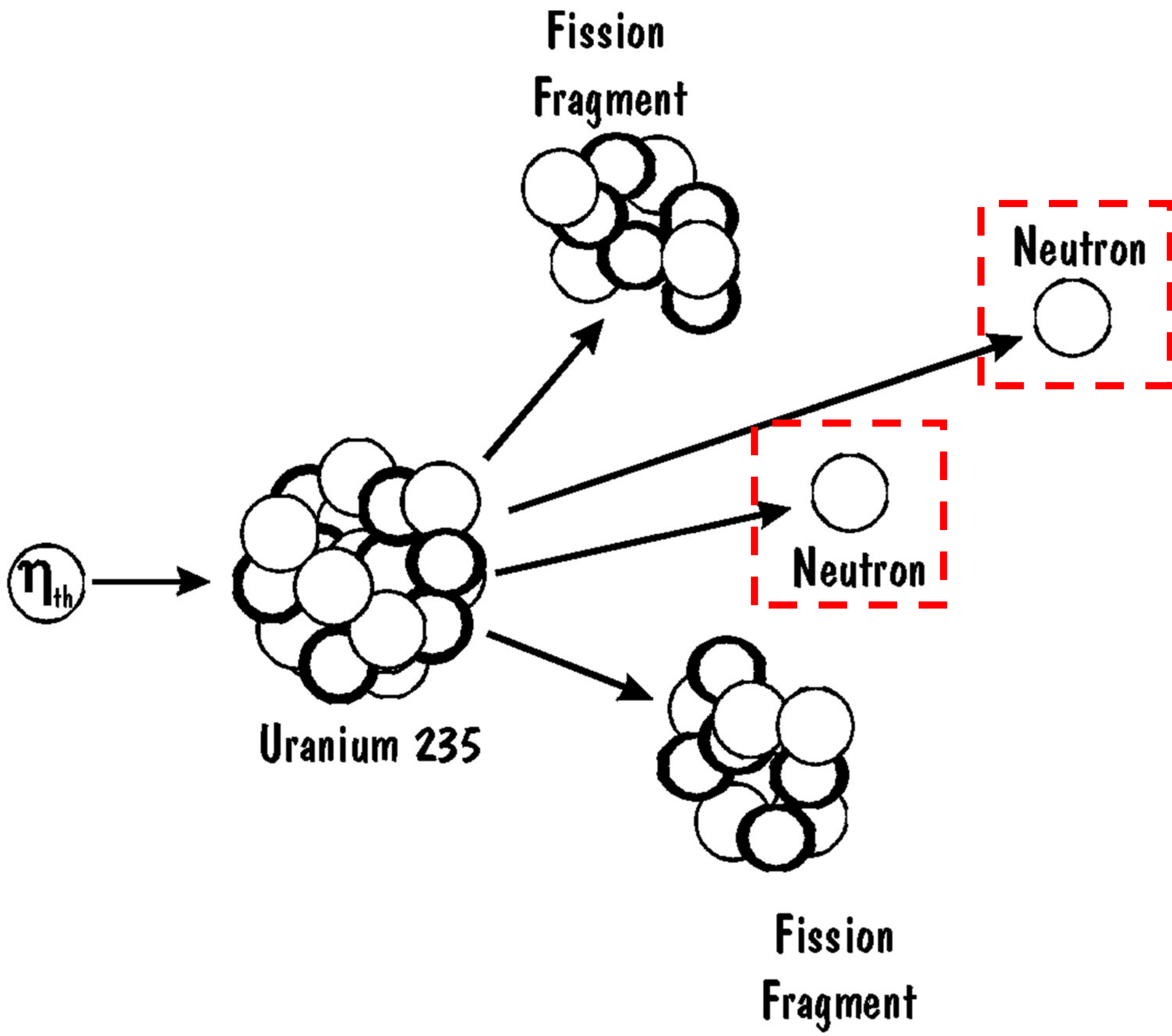
- Define fissile, fissionable, and fertile. Identify the major nuclides in each of these three categories.

- Describe the distribution of energy among the product particles and radiations associated with fission. Explain the basis for decay heat.

- Describe the energy distribution of fission neutrons.

Nuclear Fission

- Of all the nuclear reactions we have considered, fission is the most interesting
  - Occurs only in the heaviest, least stable nuclei
  - Can occur either as a natural decay mode (spontaneous fission), or due to a nuclear interaction by another particle (a neutron)
- Only the Actinides (Z ≥ 89) are large enough to allow fission
  - Only Uranium is naturally occurring (note that ^{232}Th is naturally occurring, but must first absorb a neutron to produce ^{233}U, which is fissile)
  - Only 2 total naturally occurring isotopes – ^{235}U and ^{238}U
  - Other isotopes can be artificially produced by neutron bombardment
- Two reasons that fission is so important (and valuable)
  - Large energy release per fission (200 MeV / fission)
  - Possibility of controllable self-sustaining chain reaction.



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

Sensible Energy Released During Fission

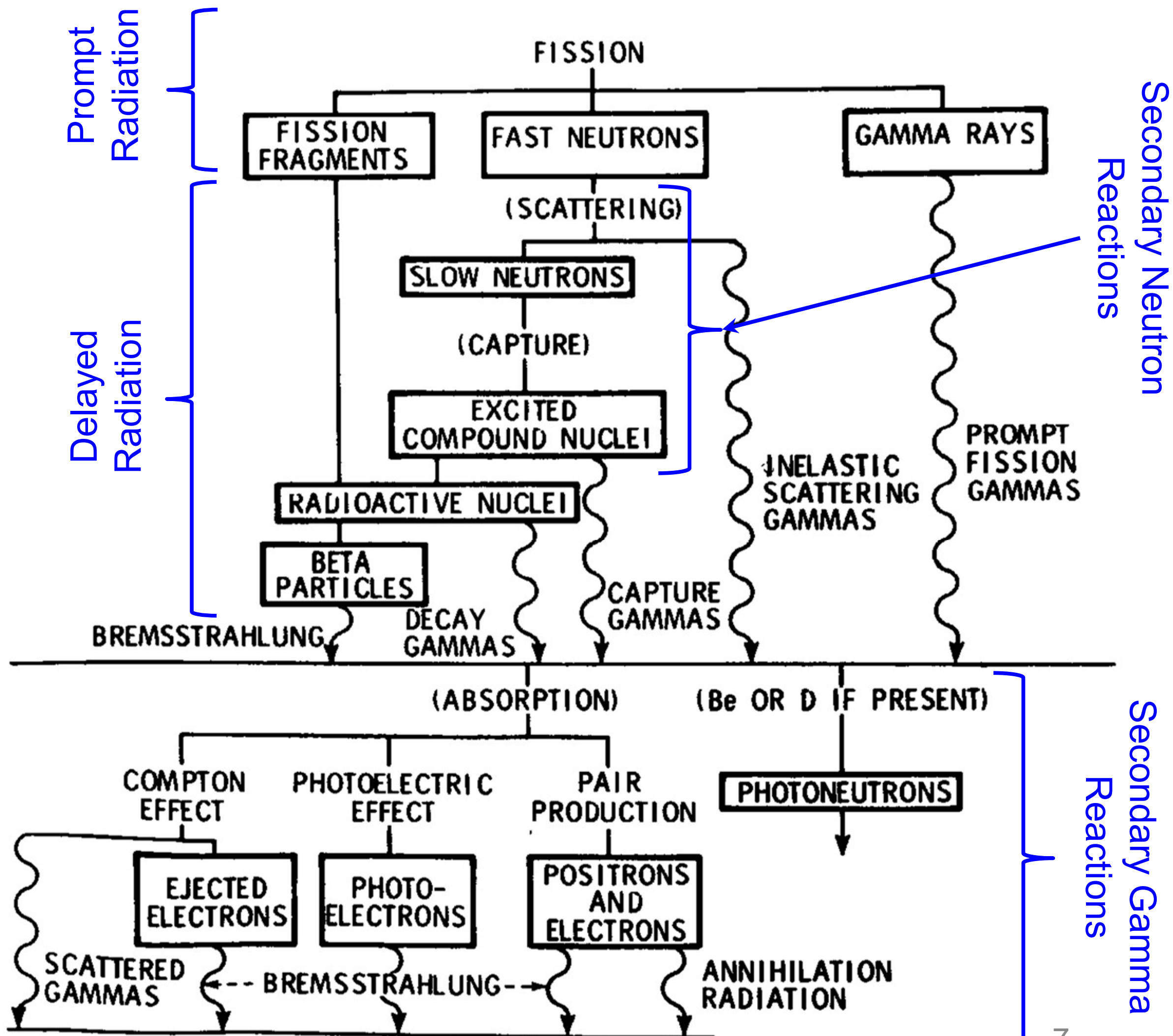
		MeV	%
Fission Fragments (Kinetic Energy)		168	84.0
Neutrons (Kinetic Energy)		5	2.5
Prompt Gamma Rays		7	3.5
Delayed Radiations			
Beta Particles*	(Kinetic Energy)	8	4.0
Gamma Rays		7	3.5
Radiative Capture Gammas		5	2.5
TOTAL		200	100

**Neutrinos account for another 12 MeV that cannot be detected*

Fissioning one uranium atom provides **nearly 100,000,000 times** as much energy as combusting one carbon atom.

Secondary Fission Radiations

- Fission reactions are extremely disruptive, producing:
- Prompt Radiation
  - Fission products
  - Free Neutrons
  - Prompt gammas
- Delayed Radiation
  - Decay of unstable fission products
  - Reactions caused by free neutrons
  - Secondary reactions



Reproduced from Knief, 1992, *Nuclear Engineering*

Student Question

- Radiation sources from nuclear power plants consist of

a) Fission fragments, prompt neutrons, and gamma radiation emitted at the time of fission

b) Gamma radiation emitted as a result of (n, γ) reactions

c) Delayed radiation from activation and transmutation products

d) All of the above

Student Question

- Q. Radiation sources from nuclear power plants consist of

a) Fission fragments, prompt neutrons, and gamma radiation emitted at the time of fission

b) Gamma radiation emitted as a result of (n, γ) reactions

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Define fissile, fissionable, and fertile. Identify the major nuclides in each of these three categories

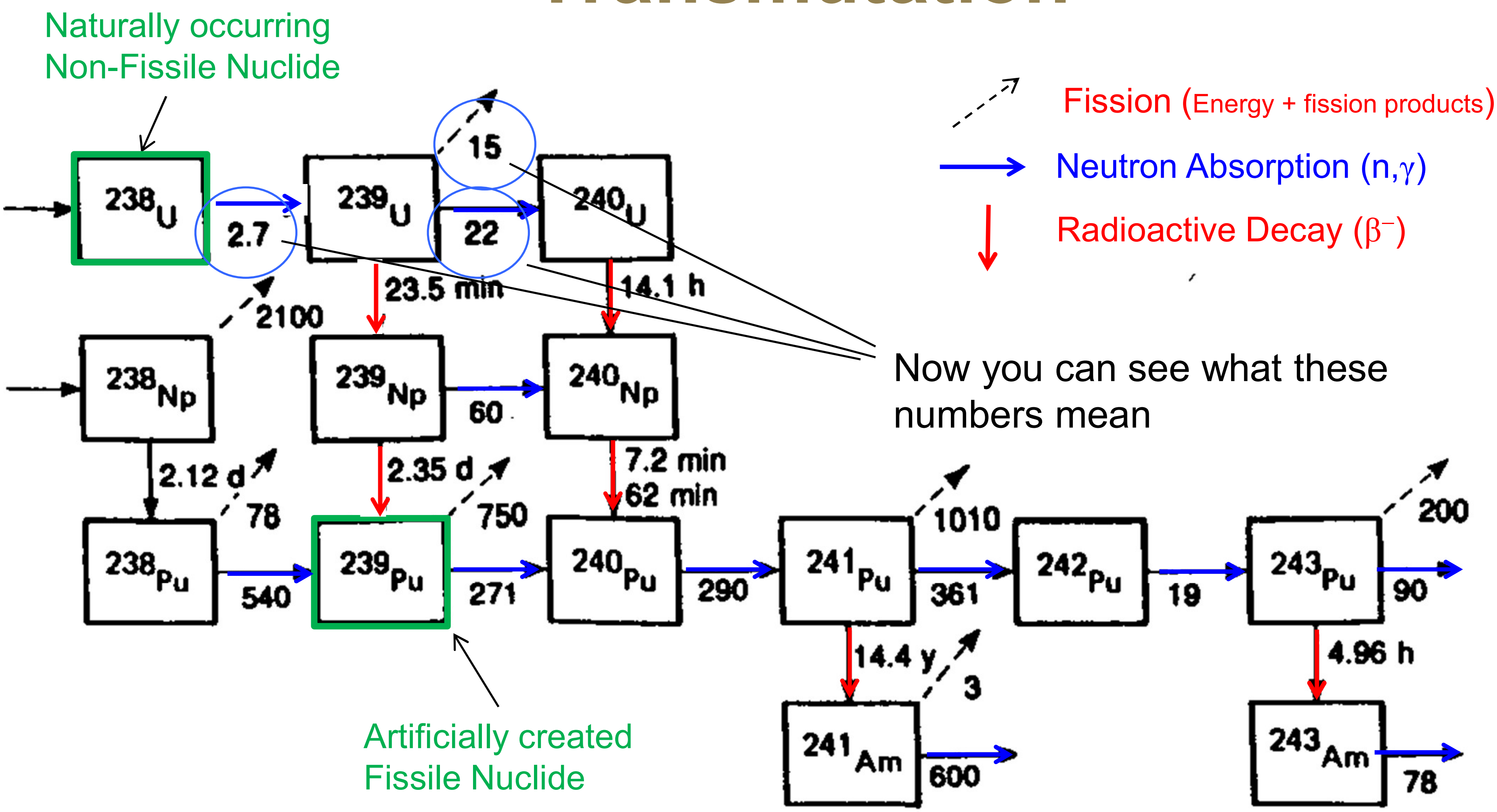
Nuclear Fission

- Nuclides in the Actinide period are classified by their potential to undergo fission events when their nucleus is struck by a neutron
- A nuclide is said to be Fissionable if neutron-induced fission is possible in the nuclide.
  - All nuclides with atomic number $Z > 89$ are fissionable.
- Fissionable nuclides are further classified as
  - Fissile, if fission can be caused by neutrons with any amount of kinetic energy (Typically even-odd, odd-even, or odd-odd)
  - Non-Fissile, if fission is a threshold reaction that can only be caused by high energy neutrons with a certain amount of kinetic energy (Typically even-even nuclides)

Nuclear Fission

- Fissile nuclides are most effective in a nuclear chain reaction because any neutron can cause an additional fission.
- Non-Fissile nuclides can only fission during reactions with high-energy neutrons.
  - Reactions involving low-energy neutrons typically involve the neutron being absorbed in an (n,γ) event.
  - However, this neutron absorption changes the number of nucleons in the nucleus, making the atom less stable.
  - In some cases, the neutron absorption can change a non-fissile nuclide into a fissile nuclide through transmutation. The original nuclide is then said to be fertile.

Transmutation



Fertile Conversion / Breeding

$$ {}^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U + {}^{0}_{0}\gamma $$

$$ \beta^{-} \downarrow \quad \text{24 m} $$

$$ {}^{239}_{93}Np $$

$$ \beta^{-} \downarrow \quad \text{2.4 d} $$

$$ {}^{239}_{94}Np $$

$$ {}^{232}_{90}Th + {}^{1}_{0}n \longrightarrow {}^{233}_{90}Th + {}^{0}_{0}\gamma $$

$$ \beta^{-} \downarrow \quad \text{22 m} $$

$$ {}^{233}_{91}Pa $$

$$ \beta^{-} \downarrow \quad \text{27 d} $$

$$ {}^{233}_{92}U $$

$$ {}^{240}_{94}Pu + {}^{1}_{0}n \longrightarrow {}^{241}_{94}Pu + {}^{0}_{0}\gamma $$

Actinide Transmutation

- Non-Fissile nuclides that can be converted to fissile nuclides by a neutron absorption reaction are referred to as fertile nuclides.
  - ^{232}Th and ^{238}U are the most common examples of fertile nuclides

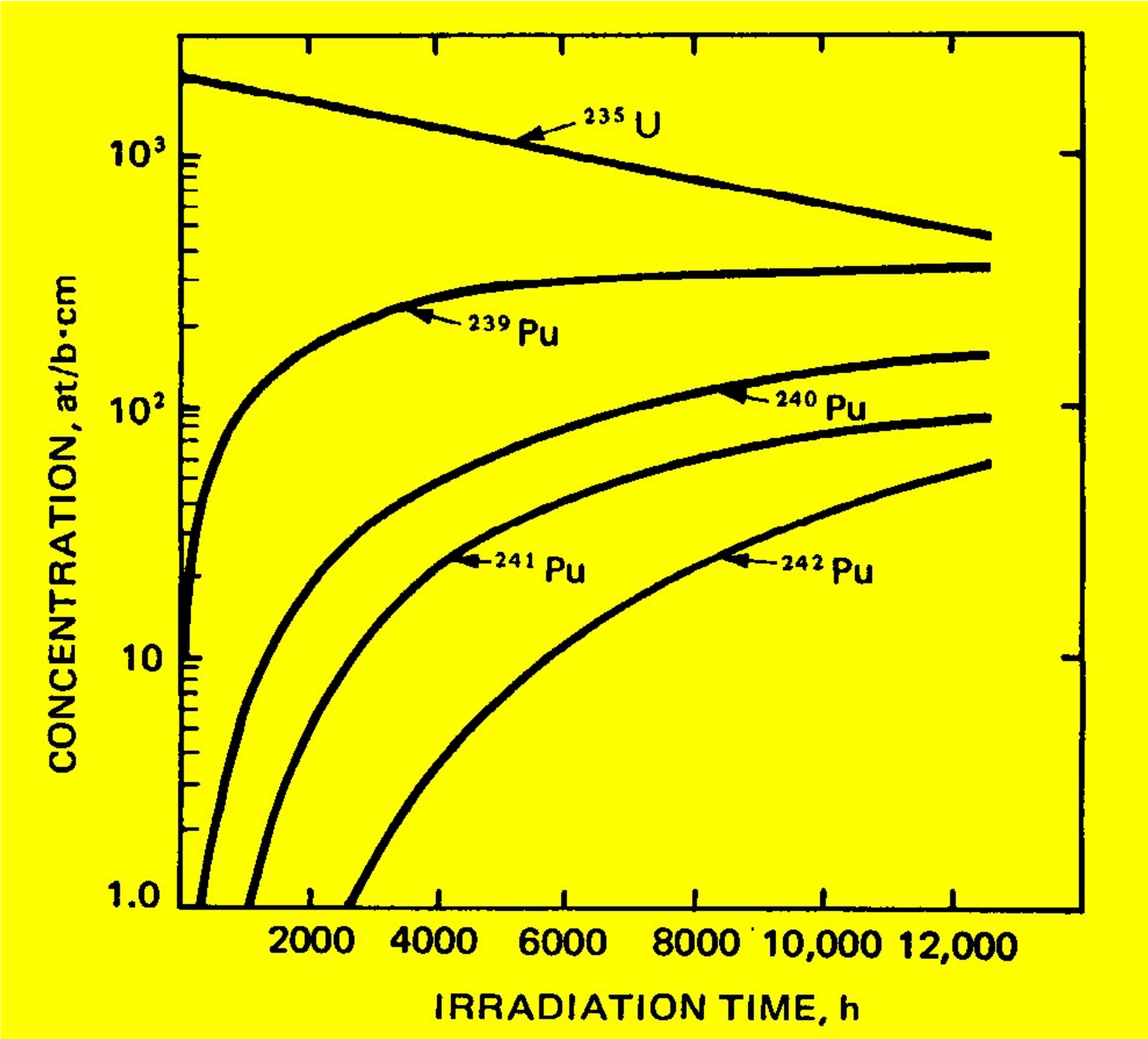
- The process of converting fertile nuclides into fissile nuclides is called conversion or breeding.
  - $^{232}Th + n \rightarrow {}^{233}U$
  - $^{238}U + n \rightarrow {}^{239}Pu$

Fissionable Nuclides

- Major Fissionable Nuclides
  - Fissile ^{235}U ^{233}U ^{239}Pu ^{241}Pu
  - Fertile ^{232}Th ^{238}U ^{240}Pu

Conversion or Breeding: $^{232}Th \rightarrow {}^{233}U$, $^{238}U \rightarrow {}^{239}Pu$, $^{240}Pu \rightarrow {}^{241}Pu$

Pu Buildup


235U
239Pu
240Pu
241Pu
242Pu
10³
10²
10
1.0
CONCENTRATION, at/b·cm
2000
4000
6000
8000
10,000
12,000
IRRADIATION TIME, h

Student Question

- Q. Which of the following nuclides is not a fissile isotope?

a) Pu-241
b) Th-232
c) U-233
d) U-235

Student Question

- Q. Which of the following nuclides is not a fissile isotope?

a) Pu-241

b) Th-232

c) U-233

d) U-235

- All the odd atomic weight nuclides in this above list are fissile. So Th-232 is not a fissile isotope. It is fertile (and fissionable). Correct answer is (b)

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Student Question

- Q. The term "fissile" applies to nuclides that:
  - a) can be fissioned by neutrons of any energy
  - b) can be fissioned by only by neutrons of high energy
  - c) upon neutron irradiation are converted (transmuted) to nuclides which are (or will become after radioactive decay) a fissile nuclide

- Q. The term "fissionable" applies to nuclides that:
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- Q. The term "fertile" applies to nuclides that:
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  - a) can be fissioned by neutrons of any energy
  - b) can be fissioned by only by neutrons of high energy
  - **c) upon neutron irradiation are converted (transmuted) to nuclides which are (or will become after radioactive decay) a fissile nuclide**

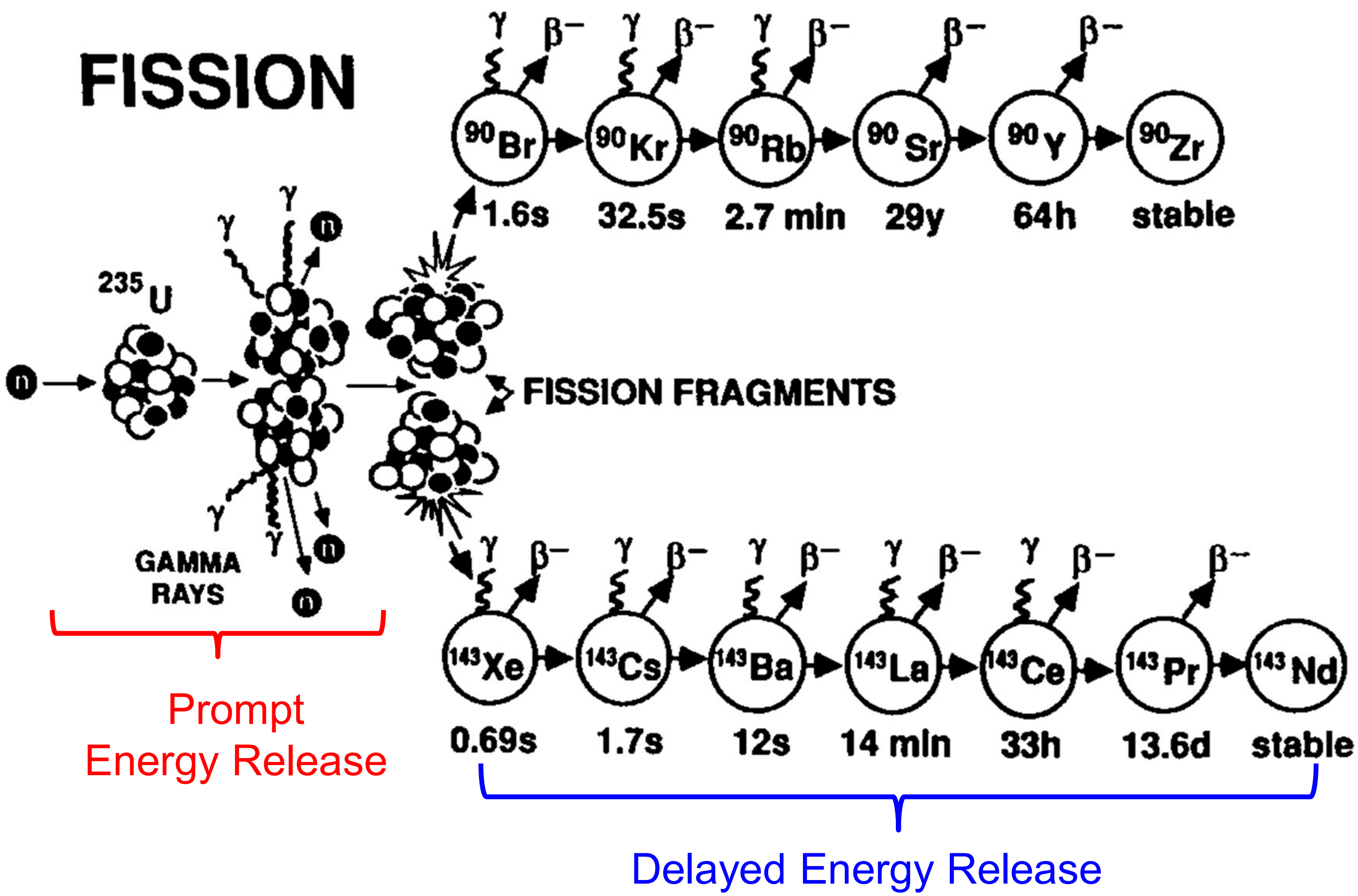
Describe the distribution of energy among the product particles and radiations associated with fission.

Explain the basis for decay heat

Energy Released During Fission

- The energy released from fission occurs in two phases
- **Prompt**
  - Energy released during the fission event
    - Kinetic energy of fission fragments, free neutrons, and ejected electrons
    - Gamma rays released during fission
- **Delayed**
  - Energy released after the fission event due to radioactive decay of fission fragments
    - Delayed gamma rays, beta particles, and neutrons
  - Delayed energy may appear milliseconds to decades or longer after a fission event.

Energy Released During Fission



Prompt Energy Release

- Accounts for ≈90% of energy released in fission
  - Kinetic energy of fission fragments (≈ 84%)
  - Kinetic energy of free neutrons (2.5%)
  - Gamma rays emitted during fission (3.5%)
- Random number of free neutrons produced in fission
  - Between 0 and 5 neutrons produced per fission
  - Average (denoted ν) between 2-3 produced per fission
- Prompt energy is divided between fission fragments and neutrons
  - Free neutrons can be produced with a wide range of initial velocities (kinetic energy).

Sensible Energy Released During Fission

	MeV	%
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TOTAL	200	100

7.5 % Max. Decay Heat

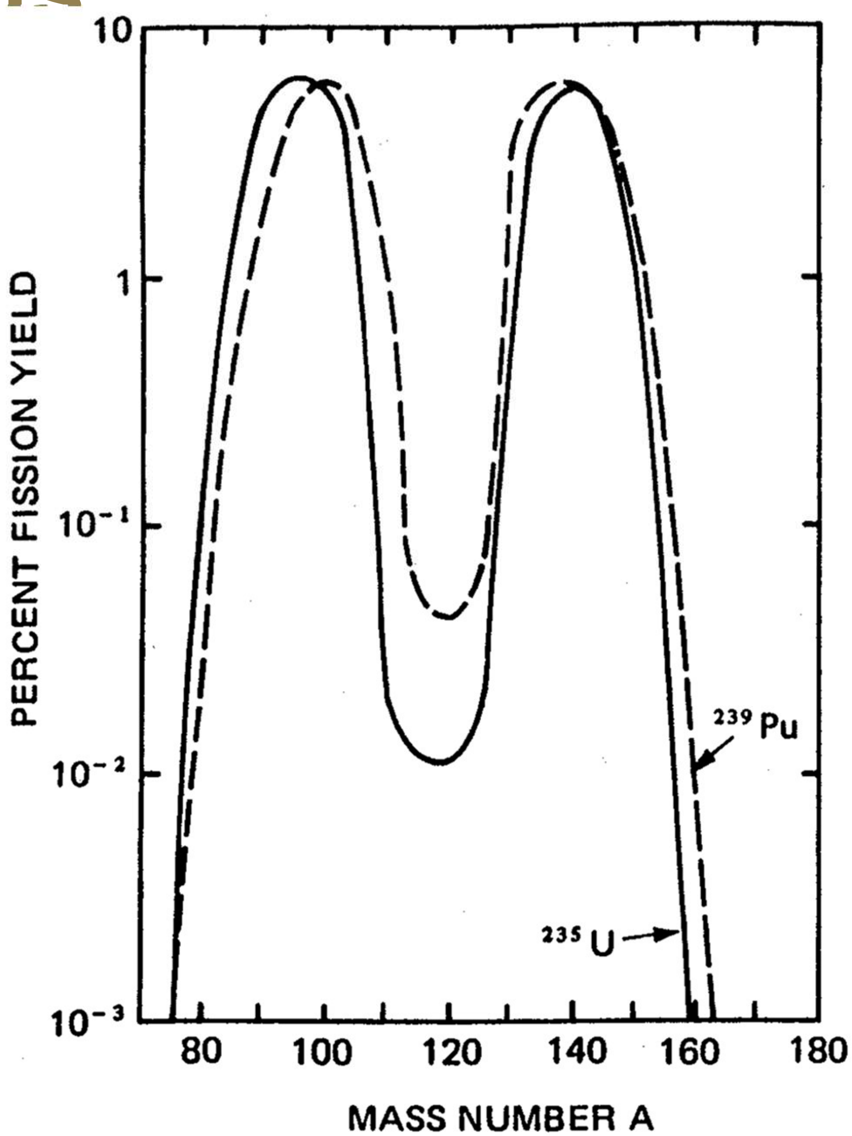
Delayed Energy Release

- Accounts for ≈10% of energy released in fission
  - Radioactive decay of unstable fission products (≈ 10%)
  - Energy may be released over hundreds of years as harmful gamma radiation.
  - Explains why spent nuclear fuel is difficult to handle.

- The type and amount of delayed radiation depends heavily on what daughter nuclei are produced during fission.
  - Fission splits original nucleus randomly into two pieces
  - Fission fragments are typically not the same size

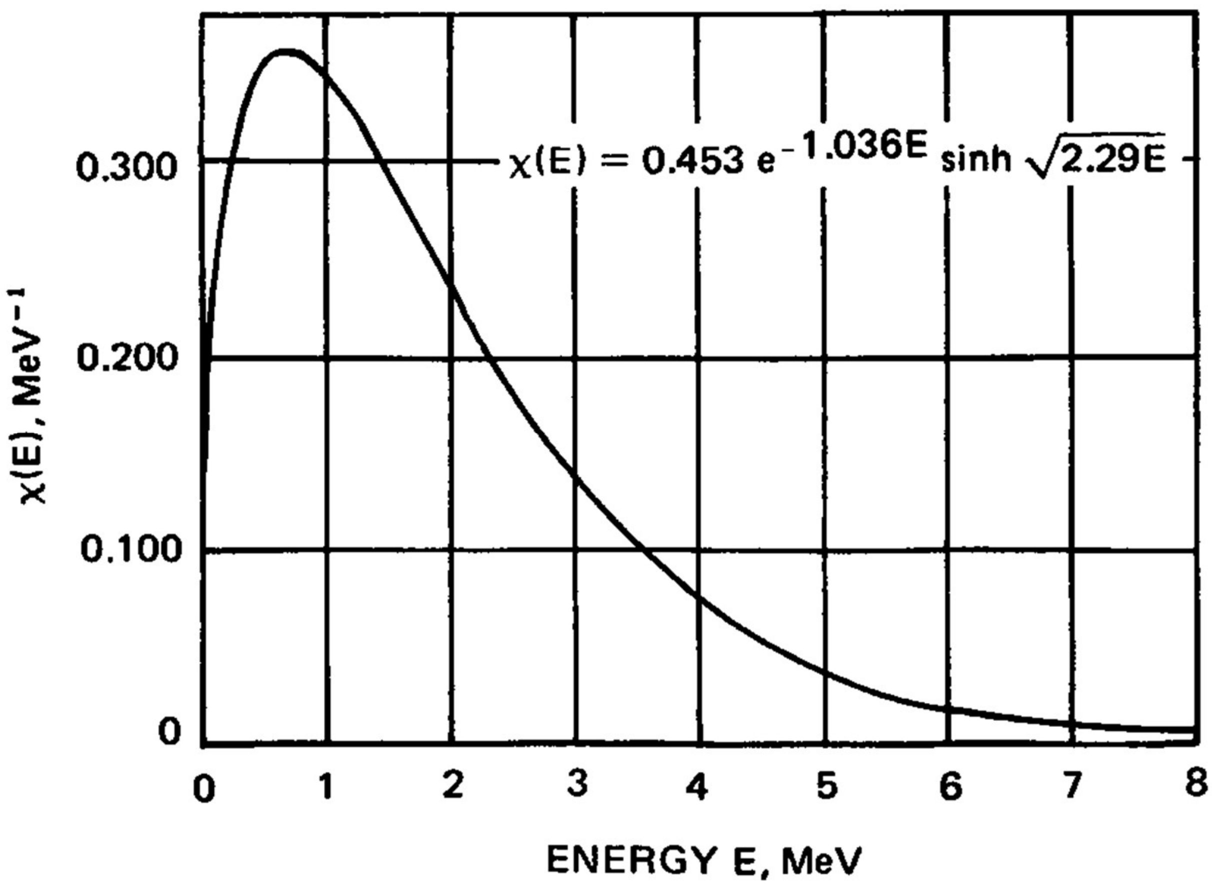
Fission Fragments

- Mass distribution of fission fragments produced during fission in ^{235}U and ^{239}Pu.
- Original nucleus is split 66/34 into daughter nuclei.



Describe the energy distribution of fission neutrons

Neutron Energy Spectrum



Fission Neutron Energy Distribution

- Energy Range:
  - 0.1 – 10 MeV
- Most Probable Energy:
  - 0.7 MeV
- Average Energy
  - 2 MeV