PennState
College of Engineering

NucE 497: Reactor Fuel Performance

Lecture 3: Fission and heat generation

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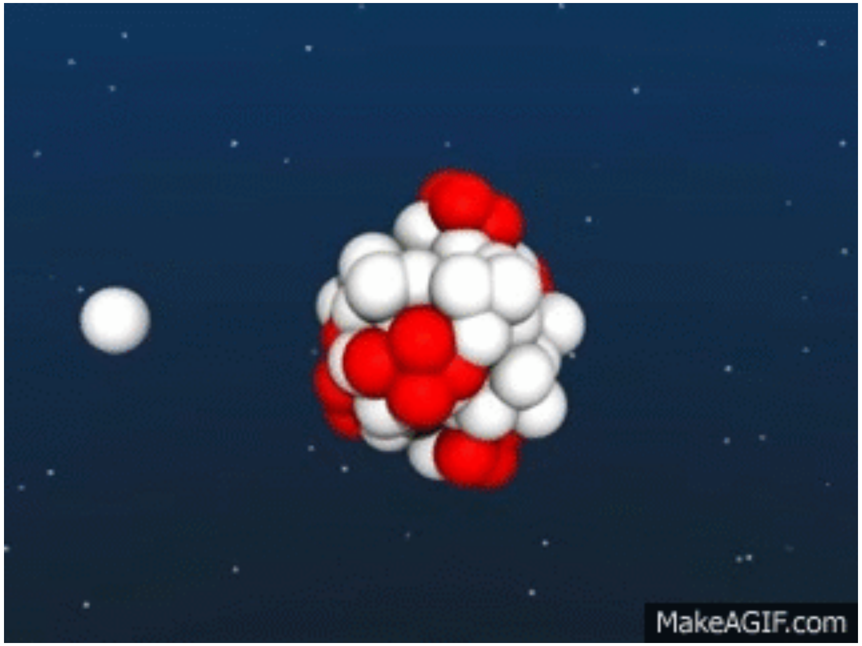
Today we will discuss fission and its products

- Module 1: Fuel basics
  - Purpose of the fuel and types of fuel
  - **Fission, heat generation, fission products**
  - Fuel geometry and the role of cladding
  - Fuel fabrication
- Module 2: Heat transport
- Module 3: Mechanical behavior
- Module 4: Materials issues in the fuel
- Module 5: Materials issues in the cladding
- Module 6: Accidents, used fuel, and fuel cycle

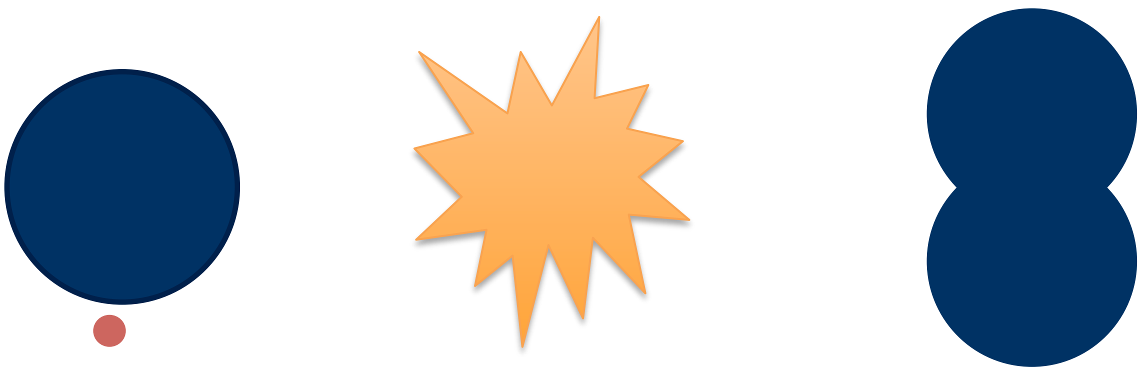
The first piece to understanding fuel performance, is understanding fission

- What initiates a fission event?



- For a fissile atom, the initiating neutron can have any energy

The bombarding neutron causes the nucleus to form two lobes and then split apart



6 MeV in ^{238}U, but 7 to 8 MeV in ^{235}U

Requires 7 to 8 MeV

Fission!

Quiz question: Fission produces many things, some good and some bad. Which is NOT a direct product of fission?

- Neutrons
- Fission fragments
- Heat
- Vacancies and interstitials

Attempts: 33 out of 33

+0.55

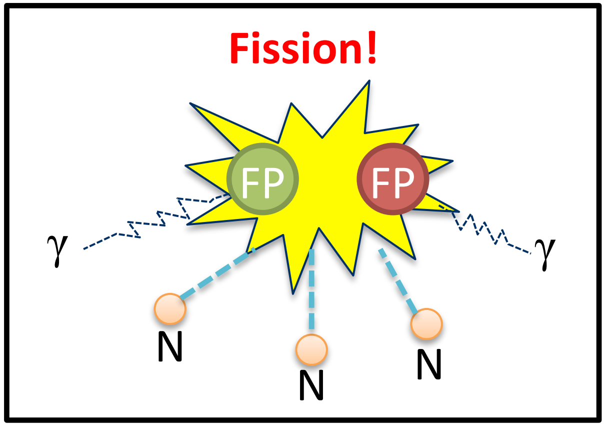
Discrimination Index

Fission produces many things, some good and some bad. Which is NOT a direct product of fission?

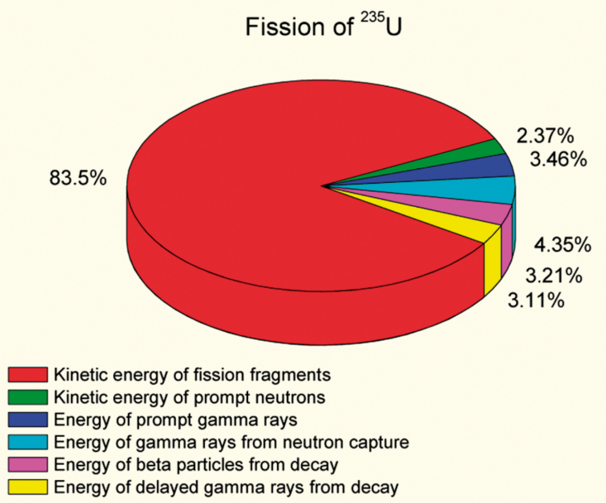
Neutrons	1 respondents	3 %
Fission fragments		0 %
Kinetic energy (eventually becomes heat)	1 respondents	3 %
Vacancies and interstitials	31 respondents	**94 %** ✓

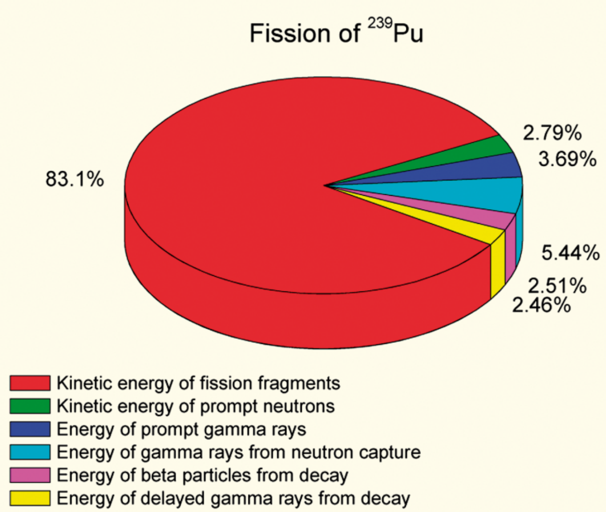
Fission has many products

- Fission releases around 200 MeV
  - The fission fragments have 169 MeV of kinetic energy
  - 2 to 3 neutrons with an average energy of 2 MeV
  - 7 MeV of prompt gamma ray photons
  - The remaining energy is released by beta decay



The energy released doesn't depend much on the nuclide that fissions



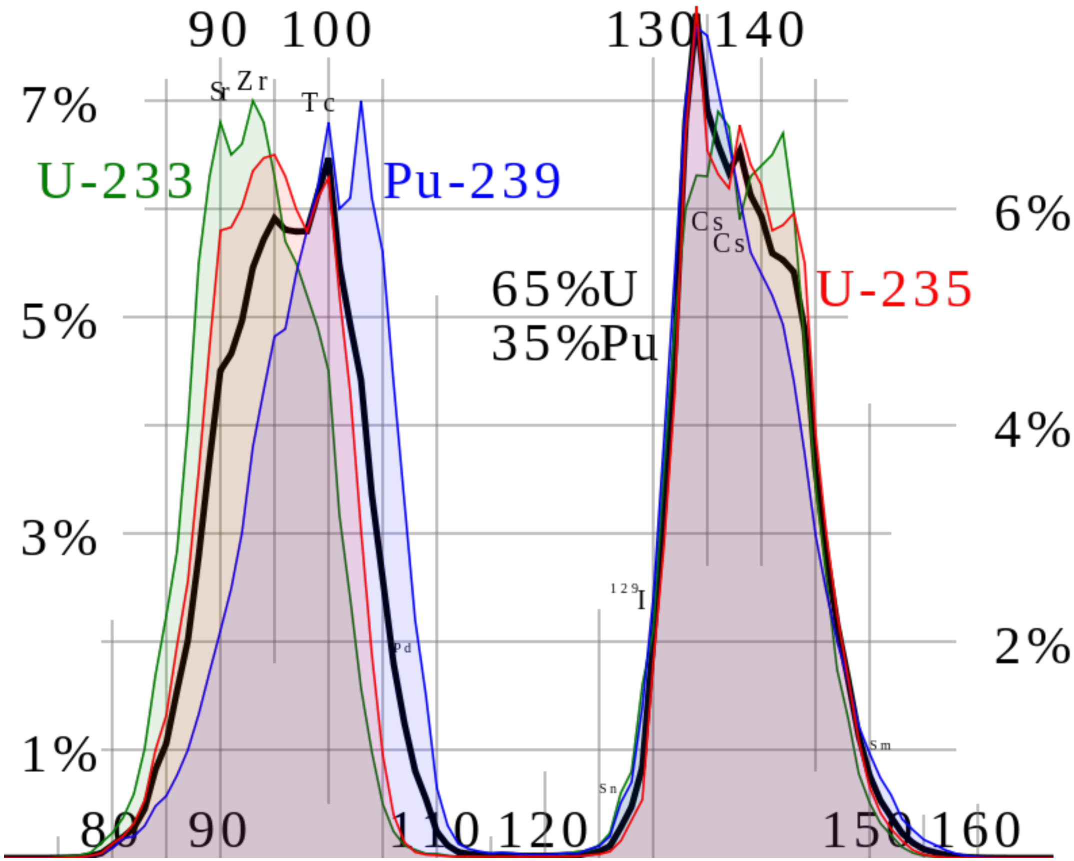


Source	Energy, MeV/f	
	^{235}U	^{239}Pu
Energy released instantaneously		
Kinetic energy of fission fragments	169.1	175.8
Kinetic energy of prompt neutrons	4.8	5.9
Energy of prompt γ-rays	7	7.8
Energy of γ-rays from nγ capture	8.8	11.5
Energy from decay of fission products		
Energy of β^--particles	6.5	5.3
Energy of delayed γ-rays	6.3	5.2
Energy of anti-neutrinos[1]	8.8	7.1
Total available energy	202.5	211.5

Note 1: Anti-neutrino energy is not absorbed in the reactor and does not contribute to the total available yield.

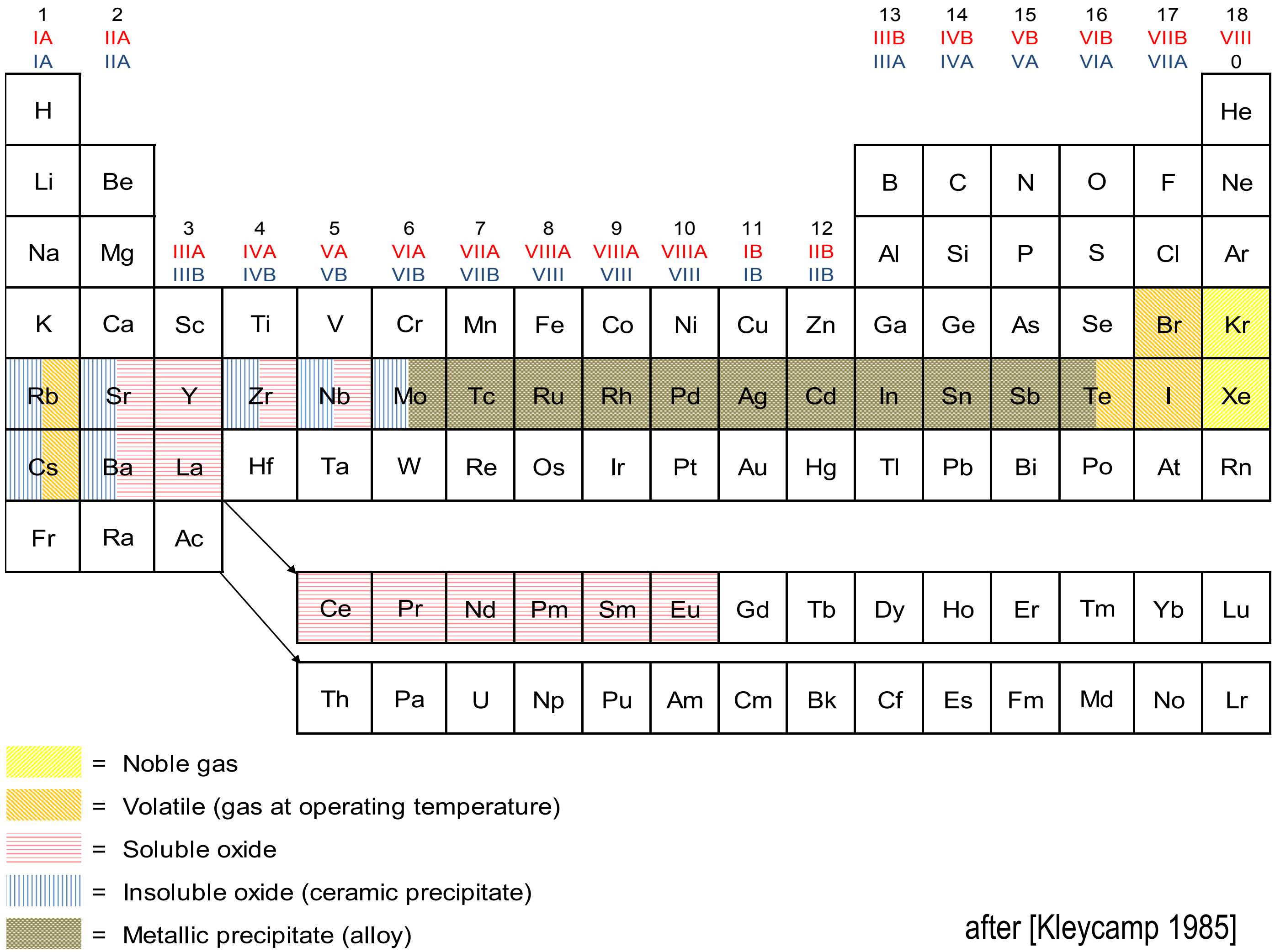
[Kaye & Laby 2005]

The type of daughter nuclei that result from the fission are stochastic



Fission product yields by mass for thermal neutron fission of U-235, Pu-239, a combination of the two typical of current nuclear power reactors, and U-233 used in the thorium cycle. (from Wikipedia)

These fission products remain in the material, resulting changes in the material



after [Kleycamp 1985]

The energy of the fission products adds heat to the material

- About 95% of the energy released from fission is converted to heat
  - $E_f = 0.95$ (200 MeV/fission) = 190 MeV/fission = 3.0×10^{-11} J/fission
- Knowing the energy converted to heat per fission, we need to determine the heat generation rate Q (W/cm^3) from the thermal neutron flux φ_{th} (n/cm^2/s)
- We also know
  - The fissioning cross section of the fissioning atom σ_f (fission/n cm^2/atom)
  - The fissile atom density N_f (atoms/cm^3)

- What is the equation for Q?
  - $Q = E_f N_f \sigma_f \varphi_{th}$
  - Units => J/fission (atoms/cm^3) (fission/n cm^2/atom) (n/cm^2/s) = J/s /cm^3

First, we need to figure out the number of fissile atoms (typically U-235) per unit volume

- How can we determine the number of atoms of U-235/cm^3?
- We will use the density δ (total g/cm^3)
    1. Determine the mass fraction $f_W = M_U/M_{UO2}$
    2. Determine density of U in UO_2, $\delta_U = f_W\, \delta$
    3. Determine number of moles of U per volume by δ_U / M_U
    4. Determine number of atoms of U per volume by $N_U = N_a\, \delta_U / M_U$
    5. Finally, $N_{U235} = q\, N_U$
- If we put it all together, we get
    - $N_{U235} = q\, N_a\, M_U/M_{UO2}\, \delta / M_U$
    - $= q\, N_a\, \delta / M_{UO2}$

We will try it out for UO_2

- For a thermal neutron flux of 3×10^{13} n/cm^2/s, calculate the heat flux in 3% enriched UO_2
- The necessary parameters are
  - The thermal fission cross section of U-235, σ_{f235} = 550 barns or 5.5×10^{-22} cm^2
  - The density of UO_2, δ = 10.97 g/cm^3
- The necessary equations are
  - $N_{U235} = q\, N_a\, \delta/M_{UO2}$ $\quad Q = E_f\, N_f\, \sigma_f\, \varphi_{th}$
- First, M_{UO2} = q 235 + (1 – q) 238 + 2 (16) = 269.85 g/mol
- N_{U235} = 0.03 (6.022e23) (10.97 g/cm^3) / (269.85 g/mol) = 7.34e20 atoms U/cm^3
- $Q = E_f\, N_f\, \sigma_f\, \varphi_{th}$ = (3e-11)(7.34e20)(5.5e-22)(3e13) = 363.3 W/cm^3

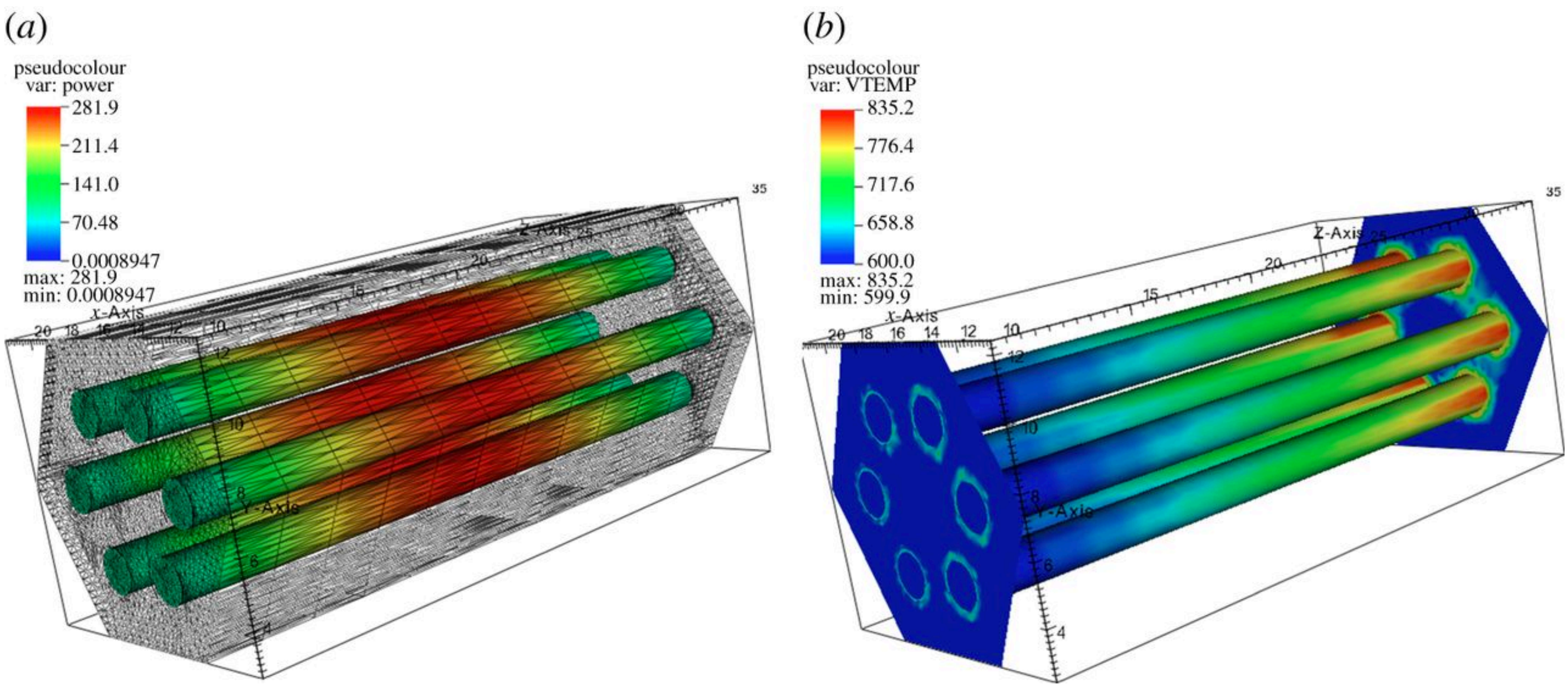
Calculate the heat flux in 3% enriched U_3Si_2 with a thermal neutron flux of 3×10^{13} $n/cm^2/s$

- $\sigma_{f235} = 5.50 \times 10^{-22}$ cm^2, $\delta_{U3Si2} = 12.2$ g/cm^3, $W_{Si} = 28.0$
- The necessary equations are $N_{U235} = 3\ q\ N_a\ \delta/M_{U3Si2}$, $Q = E_f\ N_f\ \sigma_f\ \varphi_{th}$
- NOTE: the 3 is because there are 3 uranium atoms in each molecule

- First calculate M_{U3Si2}
  - M_{U3Si2} = 3*(0.03*235 + 0.97*238) + 2*28.0 = 769.73 g/mol
- Then calculate N_{U235}
  - N_{U235} = 3*0.03*6.022e23*12.2/769.73 = 8.59e20 atoms U235/cm^3
- Finally, we calculate Q
  - Q = 3e-11*8.59e20*5.5e-22*3e13 = 425.20 W/cm^3

The neutron flux (and power profile) varies axially and radially

- Because the neutron flux varies axially, the temperature does too
- The neutron flux also varies across the radius by about 5%
  (due to self shielding)



Summary

- Fission produces kinetic energy
  - Fission fragments
  - Neutrons
  - Gammas
  - Beta decay
- The kinetic energy causes heat that we can calculate