PennState
College of Engineering

NucE 497: Reactor Fuel Performance

Lecture 2: Purpose of the fuel

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Today we will discuss the purpose of fuel, fissile and fissionable materials, and common fuels

- 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

Quiz question: What is the primary purpose of the reactor fuel in a nuclear reactor?

- Maintain a stable fission reaction
- Avoid melting
- Heat the coolant
- To glow

Attempts: 33 out of 33

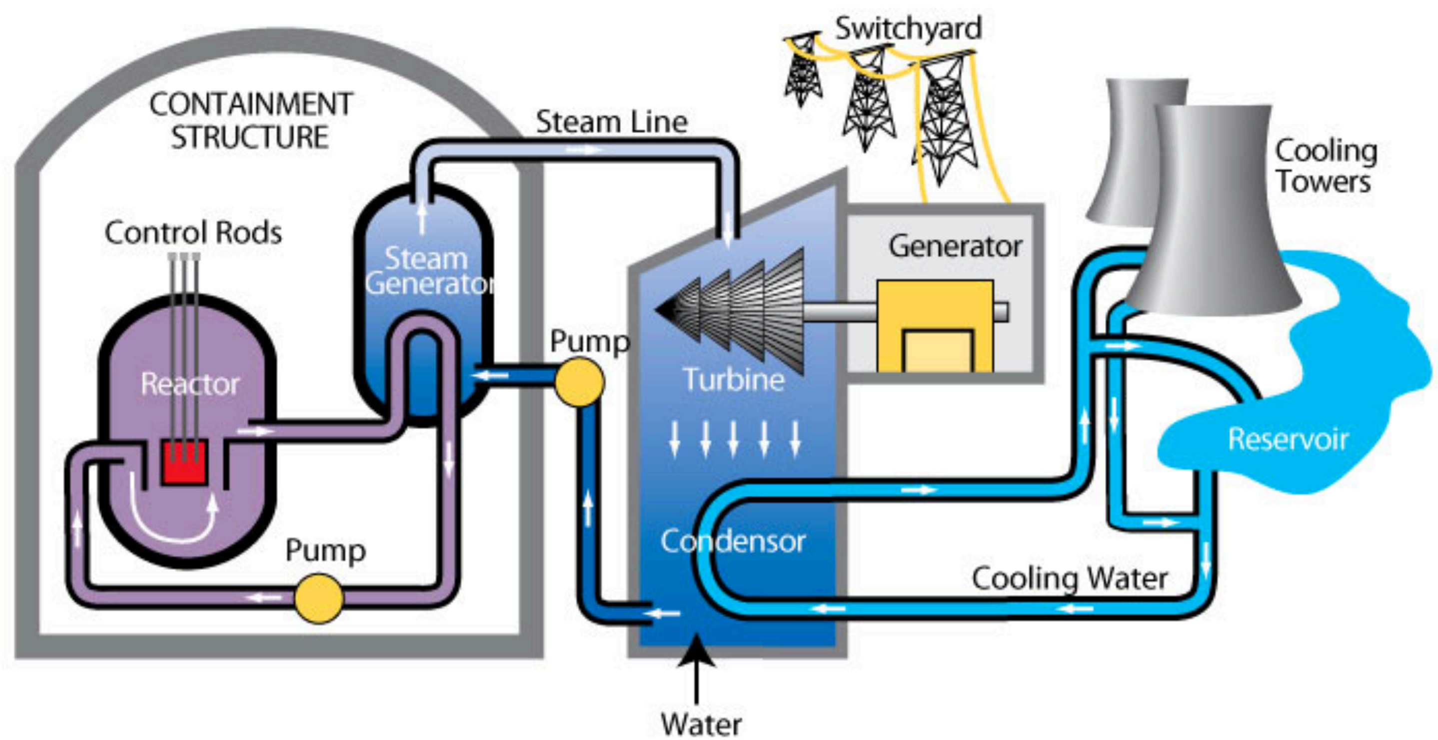
+0.83

Discrimination Index

What is the primary purpose of the reactor fuel in a nuclear reactor?

Maintain a stable fission reaction	6 respondents	18 %
Avoid melting		0 %
Heat the coolant	27 respondents	82 % ✓
To glow		0 %

The purpose of the fuel is to generate heat, through fission, and transport it to the coolant



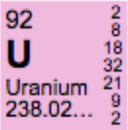
Only certain materials can be used as nuclear fuel

- A **fissionable nuclide** is capable of undergoing fission (even with a low probability) after capturing a high energy neutron
- A **fissile nuclide** is capable of sustaining a nuclear fission chain reaction with neutrons of any energy

- The **fissile rule** states that for a heavy element with $90 \leq Z \leq 100$, its isotopes with $2 \times Z - N = 43 \pm 2$ are fissile (with some exceptions)

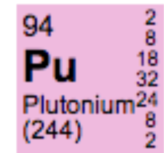
Let's try out the fissile rule

- The heavy elements with $90 \leq Z \leq 100$
  - Thorium (Th), Protactinium (Pa), Uranium (U), Neptunium (Np), Plutonium (Pu), Americium (Am), Curium (Cm), Berkelium (Bk), Californium (Cf), Einstenium (Es) and Fermium (Fm)



- First, we will apply the fissile rule to U ($2 \times Z - N = 43 \pm 2$)
  - $N = 2Z - (43 \pm 2)$
  - $N = 2 \times 92 - [41, 42, 43, 44, 45] = [143, 142, 141, 140, 139]$ neutrons
  - So, U-231 through U-235 should be fissile

Now you try out the fissile rule on Pu



- What isotopes of Pu are fissile according to the fissile rule?
  - $2 \times Z - N = 43 \pm 2$

- $N = 2 \times Z - (43 \pm 2)$
- $N = 2 \times 94 - (43 \pm 2)$
- N = 143, 144, 145, 146, and 147
- Fissile Pu isotopes are Pu-237 through Pu-241

Quiz question: Which are fissile nuclides?

- U-238
- U-235
- Th-232
- U-233
- Pu-238
- Pu-239
- Pu-241

Attempts: 33 out of 33

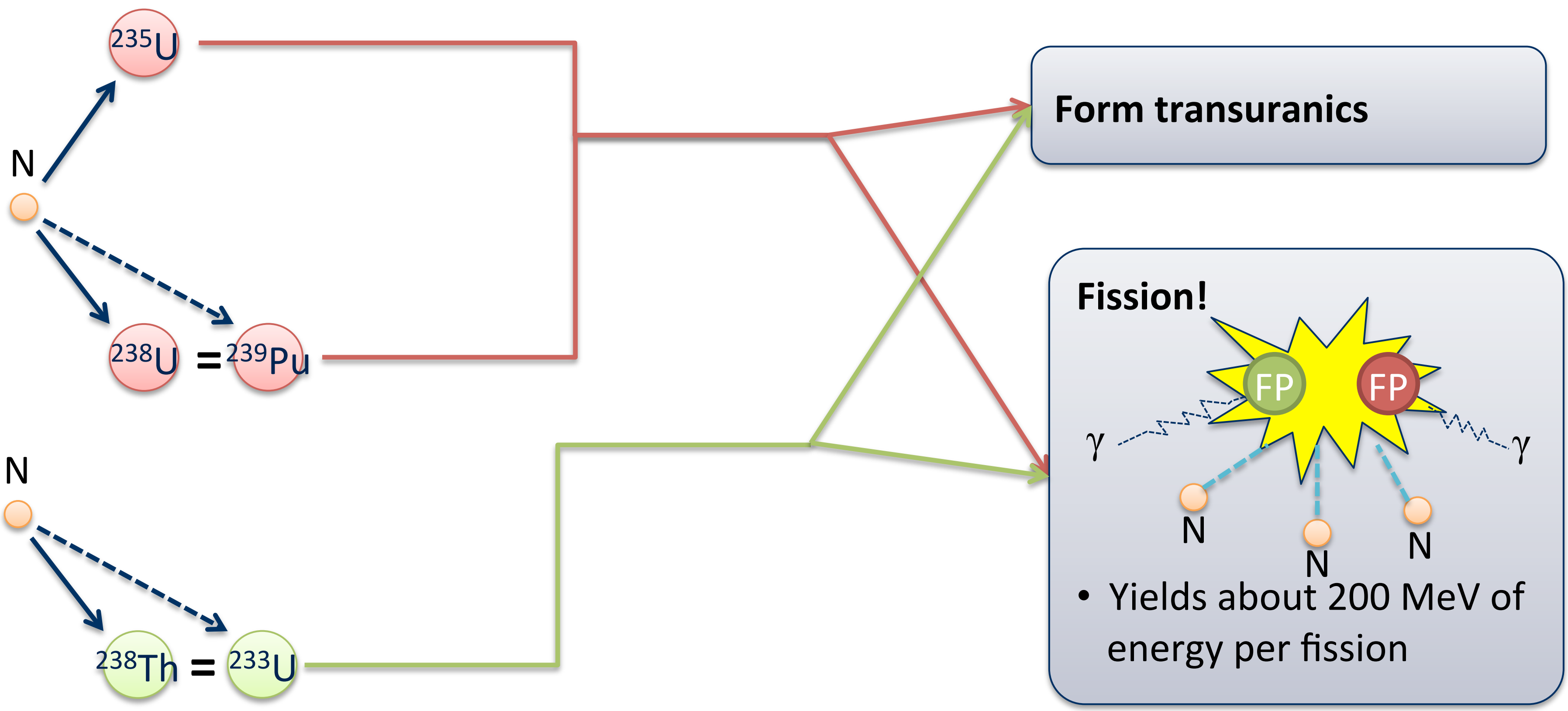
Which are fissile nuclides? Check all that apply

U-238	2 respondents	6 %
U-235	33 respondents	100 % ✓
Th-232	2 respondents	6 %
U-233	31 respondents	94 % ✓
Pu-238		0 %
Pu-239	33 respondents	100 % ✓
Pu-241	30 respondents	91 % ✓

There are only four fissile nuclides that are practical for nuclear fuel

- U-235
  - Naturally occurs in uranium in small amounts (0.7%). Can be enriched
- Pu-239
  - Bred from U-238 by neutron capture
  - $^{238}\mathrm{U} + n \xrightarrow{\gamma} {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$
- Pu-241
  - Bred from Pu-240 (which comes from Pu-239) by neutron capture
  - $^{240}\mathrm{U} + n \rightarrow {}^{241}\mathrm{Pu}$
- U-233
  - Bred from Th-232 by neutron capture
  - $^{232}\mathrm{Th} + n \xrightarrow{\gamma} {}^{233}\mathrm{Th} \xrightarrow{\beta} {}^{233}\mathrm{Pa} \xrightarrow{\beta} {}^{233}\mathrm{U}$

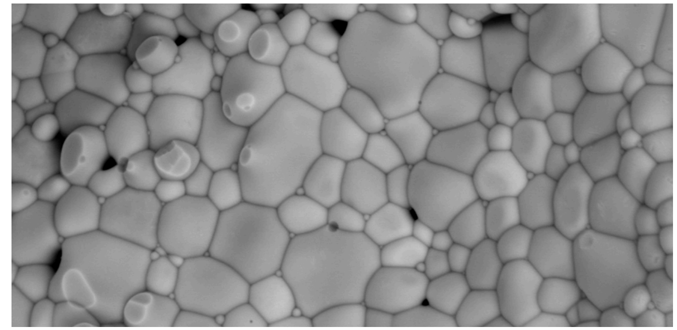
There are two viable fuel materials, uranium and thorium



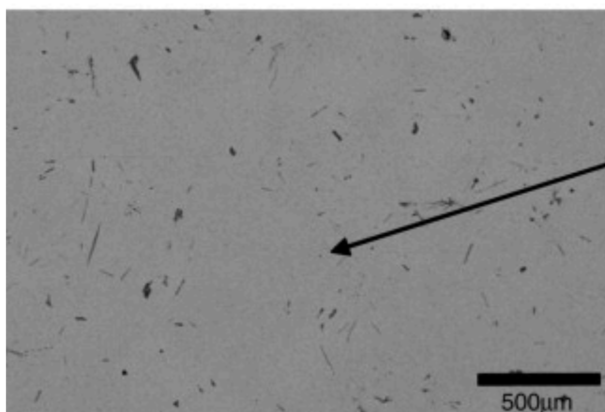
- Thorium has never been used in a commercial reactor
- Several possible thorium reactors are being considered in other countries

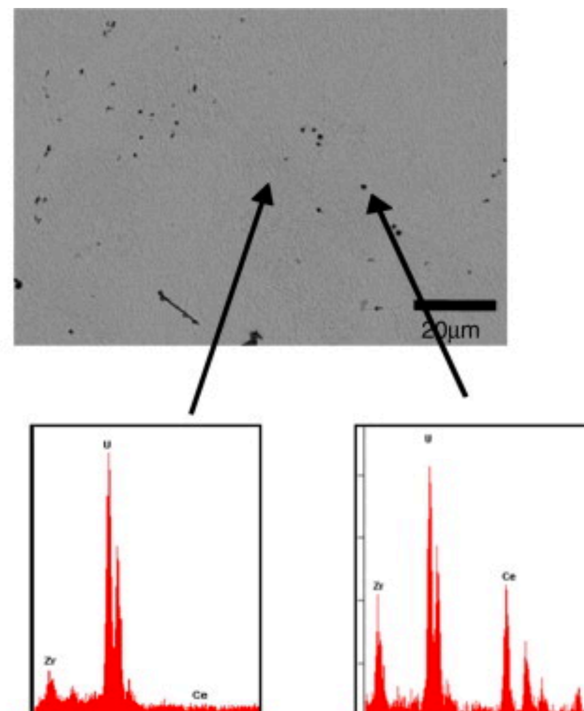
Reactor fuel has been made from various forms of uranium

- Metal
- Oxide
- Carbide
- Nitride
- Silicide



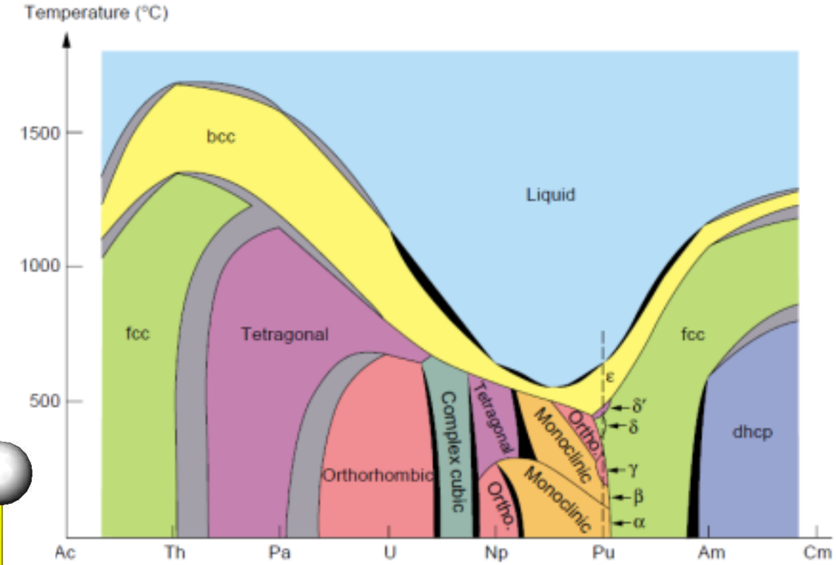
Oxide fuel microstructure



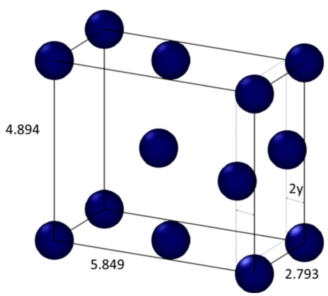


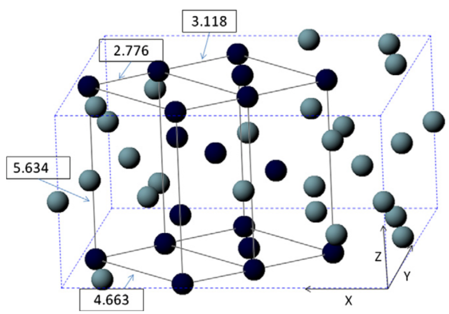
Metal fuel microstructures

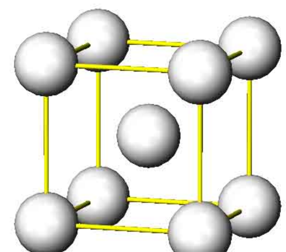
Pure uranium metal is not a viable fuel due to dimensional changes



- Pure uranium has three phases
  - α-phase is orthorhombic
  - β-phase is tetragonal
  - Y-phase is BCC (body centered cubic)

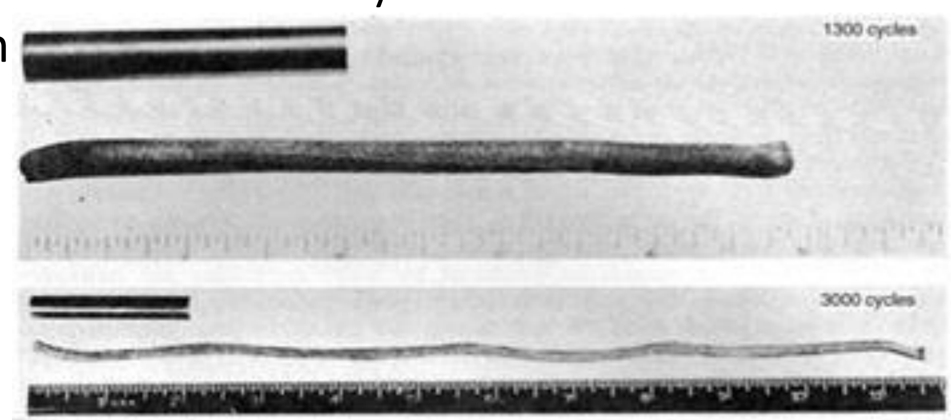






- During thermal cycling, pure uranium elongates in one direction
- Phase changes between the α and β phases causes fracture and void formation

1300 cycles between 50 and 500

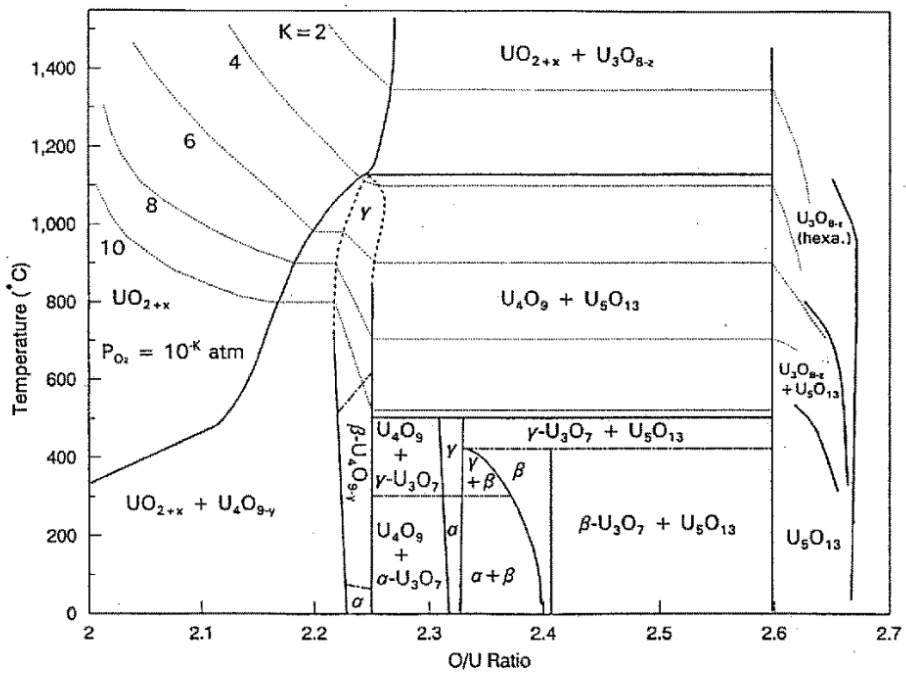


3000 cycles between 50 and 500

Alloyed metallic uranium is a viable fuel for thermal and fast reactors

- Alloying elements stabilize the γ phase at low temperature.
- Common alloys are
  - U-10%Mo – U-15%Mo
  - U-10%Zr – U-15%Zr
  - U-Pu-Zr
- Neutron absorption by Mo and Zr necessitate enrichment or fast neutrons
- Advantages
  - High fuel density
  - High thermal conductivity
  - Passive safety (due to high thermal expansion)
- Disadvantages
  - Low melting temperature
  - High swelling
  - Intermixes with Zr cladding

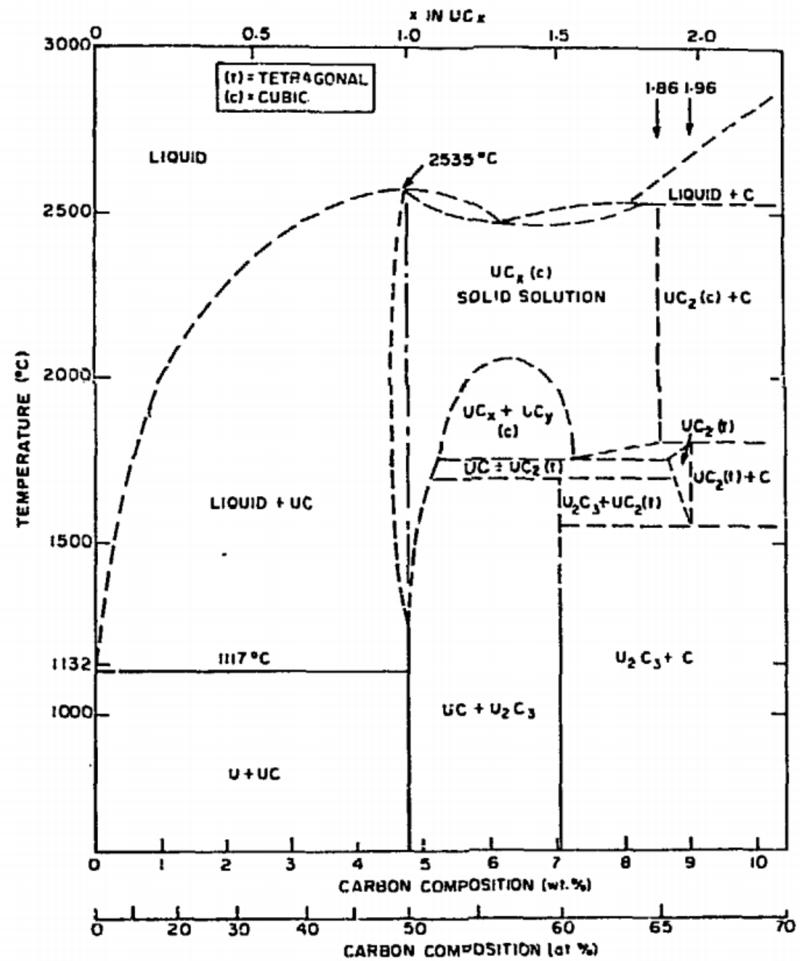
Uranium oxide is the most common fuel type, and is used in thermal and fast reactors



- The actual form is UO_2
- Advantages
  - High melting temperature
  - Chemical and structural stability
  - Compatibility with Zr-alloy cladding materials
  - Corrosion resistant in reactor water
- Disadvantages
  - Lower density of fissile atoms relative to other fuel materials
  - Low thermal conductivity
  - Higher stored thermal energy than other fuel materials

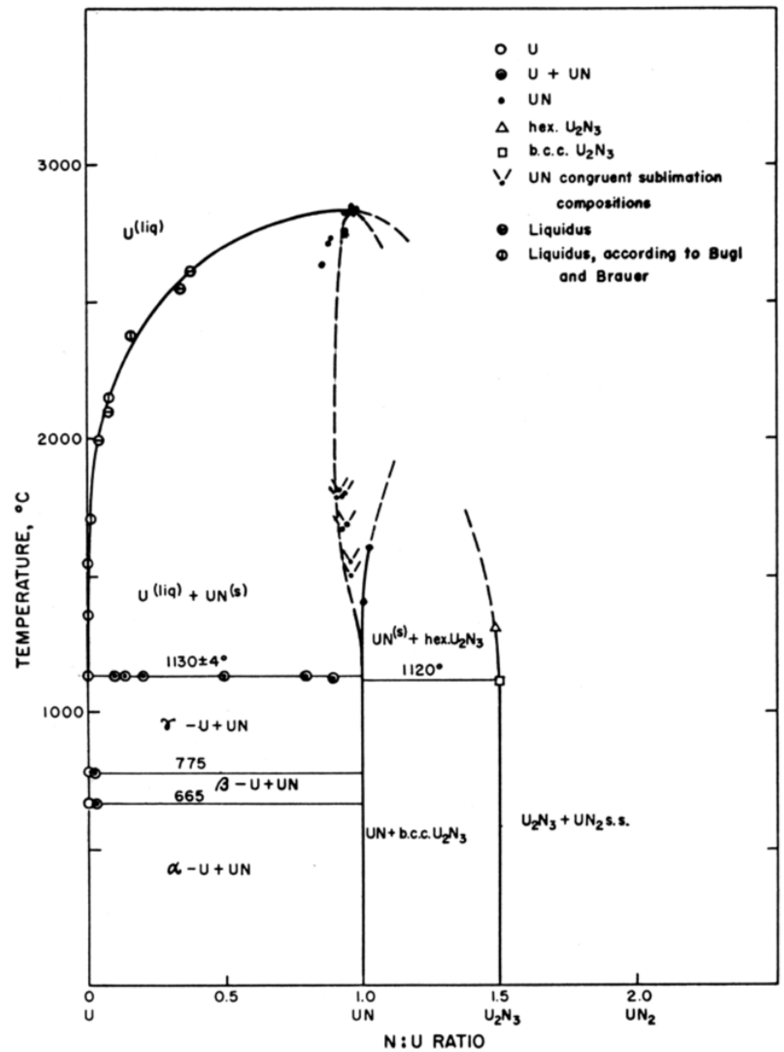
Uranium carbide has some benefits and has been used in TRISO fuel particles

- Can appear as UC, U_2C_3, or UC_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Rapidly corrodes in water
  - Reacts with some cladding



Uranium nitride also has some benefits and is being considered as new fuel in LWRs

- Can appear as UN, U_2N_3, or UN_2
- Advantages
  - High thermal conductivity
  - High fuel density
  - Thermally stable
  - High melting temperature
- Disadvantages
  - Corrodes in water
  - Reacts with some cladding



Uranium silicide is also being considered due to its better interactions with water

- Can U_3Si, U_3Si_2, USi, U_3Si_5, or USi_3
- Advantages
    - High thermal conductivity
    - Higher fuel density
    - Thermally stable
- Disadvantages
    - Has moderate corrosion resistance
    - Reacts with some cladding
    - Has a lower melting temperature

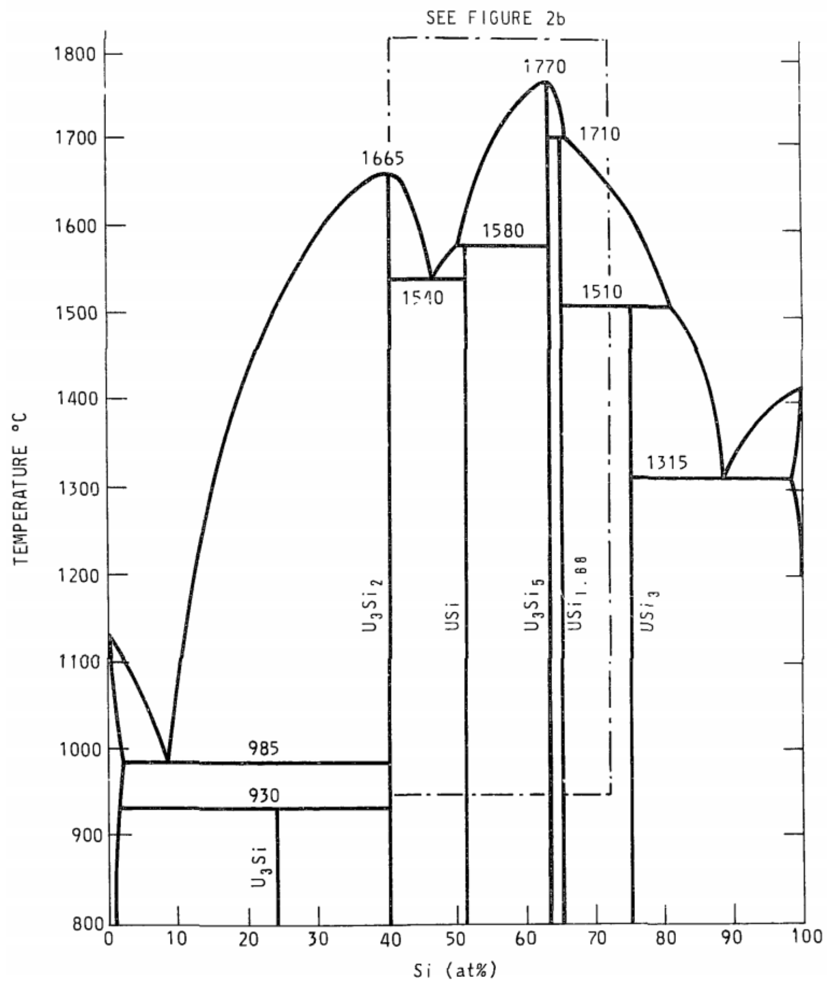


FIGURE 2 URANIUM SILICON EQUILIBRIUM DIAGRAM

What are possible reasons for why we primarily use UO_2 for reactor fuel?

Property	*Metal*	*UO_2*	*UC*	*UN*	*U_3Si_2*
A. Chemical					
Corrosion resistance in water	Very poor	Excellent	Very poor	Poor	Moderate
Compatibility with clad materials	Reacts with normal clad	Excellent	Variable	Variable	Variable
Thermal stability	Phase change at 665 and 770 °C	Good	Good in reducing atmosphere	Good, decomposes at 2600 °C	Good
B. Physical					
Uranium (metal) density (g/cm^3)	19.04	9.65	12.97	13.52	11.31
Melting point (°C)	1132	2865	2850	2860	1665
Thermal conductivity (W/cmK)	0.38 at 430 °C	0.03 at 1000°C	0.25 at 100 – 700°C	0.2 at 750°C	0.23 at 773°C

after Garzarolli in [Rudling, et al. 2007]

Summary

- The purpose of reactor fuel is to generate heat from fission
- Fissile nuclides are capable of sustaining a nuclear fission chain reaction with neutrons of any energy
  - U-233
  - U-235
  - Pu-239
  - Pu-241
- Uranium is primarily used for fuel, but is used in various forms:
  - Metal
  - Oxide
  - Carbide
  - Nitride
  - Silicide