

# Nuclear Fuel Performance

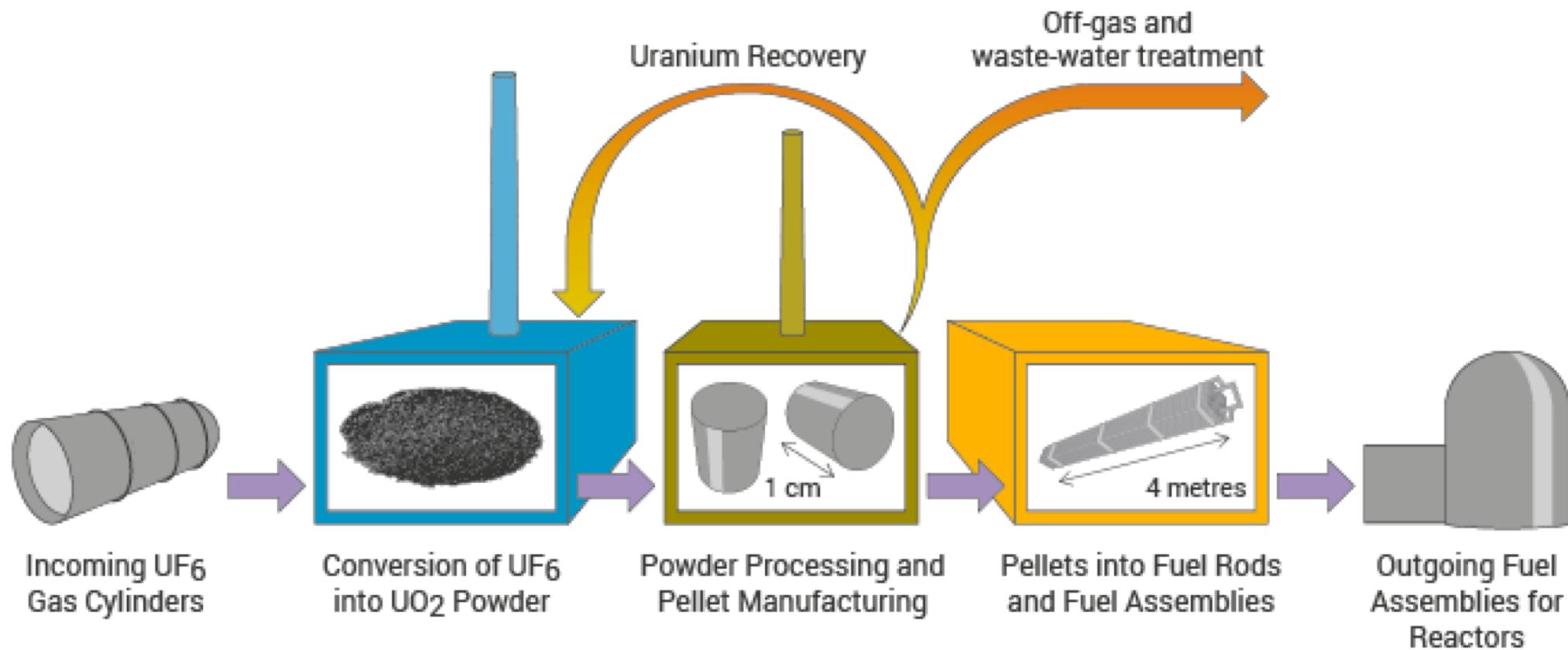
NE 591

# Last Time

- Worked through energy release from fission
- Heat generation:  $Q = E_f \times N_f \times \sigma_f \times \phi$
- Summarized reactor systems
  - Fuel-Cladding-Coolant
- All reactors have basic requirements they must meet
  - Remove the heat; Convert to electricity; Contain fission products; Cycle the fuel; Containment

# FUEL FABRICATION

# Fabrication Process



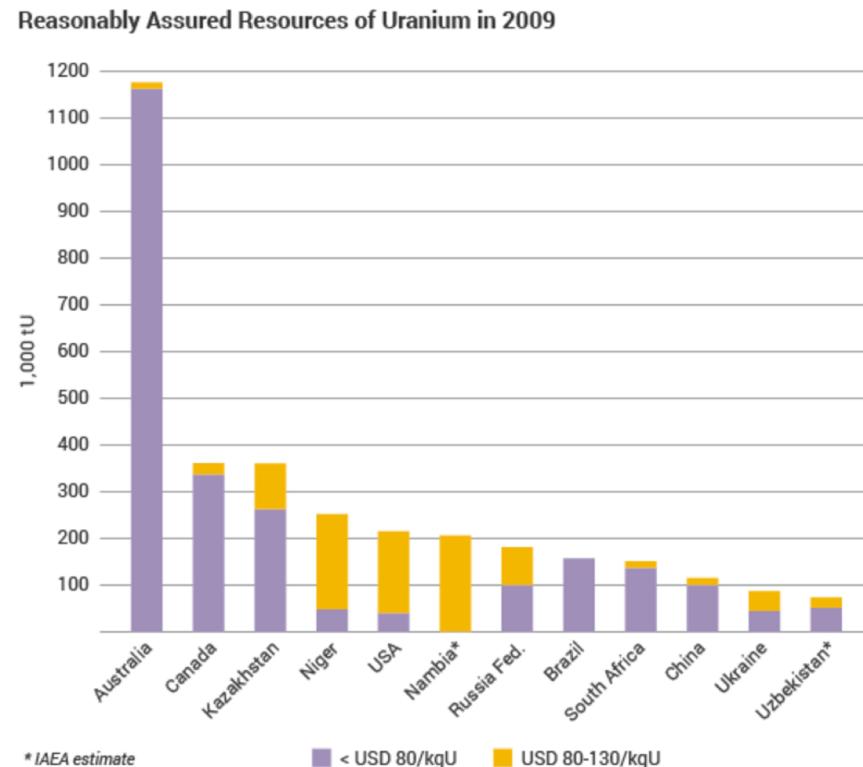
# Uranium deposit types

- There are mainly three types of uranium deposits
  - Sedimentary
    - Often found in sandstone; common in Canada and western US
  - Igneous/hydrothermal
    - Vein-type uranium ores from geothermal activity; Greenland and Namibia
  - Breccial
    - found in rocks that have been broken due to tectonic fracturing, or weathering; common in India, Australia and the US
- Less common means of uranium mining include seawater recovery, where U concentrations is 3.3 micrograms per liter

# Global Uranium Resources

Table 1: Typical natural uranium concentrations

Very high-grade ore (Canada) – 20% U	200,000 ppm U
High-grade ore – 2% U	20,000 ppm U
Low-grade ore – 0.1% U	1000 ppm U
Very low-grade ore* (Namibia) – 0.01% U	100 ppm U
Granite	3-5 ppm U
Sedimentary rock	2-3 ppm U
Earth's continental crust (av)	2.8 ppm U
Seawater	0.003 ppm U



Known Recoverable Resources of Uranium 2015

	tonnes U	percentage of world
Australia	1,664,100	29%
Kazakhstan	745,300	13%
Canada	509,000	9%
Russian Fed	507,800	9%
South Africa	322,400	6%
Niger	291,500	5%
Brazil	276,800	5%
China	272,500	5%
Namibia	267,000	5%
Mongolia	141,500	2%
Uzbekistan	130,100	2%
Ukraine	115,800	2%
Botswana	73,500	1%
USA	62,900	1%
Tanzania	58,100	1%
Jordan	47,700	1%
Other	232,400	4%
<b>World total</b>	<b>5,718,400</b>	

# Uranium mining/processing

- Uranium ores are normally processed by grinding the ore materials to a uniform particle size and then treating the ore to extract the uranium by chemical leaching
- The milling process commonly yields dry powder-form material consisting of “yellowcake”, which is  $\text{U}_3\text{O}_8$



# Conversion

- Uranium enrichment requires uranium as uranium hexafluoride, which is obtained from converting uranium oxide to  $\text{UF}_6$
- Uranium oxide can be reduced by hydrogen to produce  $\text{UO}_2$ 
  - $\text{U}_3\text{O}_8 + 2\text{H}_2 \implies 3\text{UO}_2 + 2\text{H}_2\text{O}$
- The oxide is then reacted with hydrogen fluoride to form uranium tetrafluoride ( $\text{UF}_4$ )
  - $\text{UO}_2 + 4\text{HF} \implies \text{UF}_4 + 2\text{H}_2\text{O}$
- The tetrafluoride is then fed into a fluidized bed reactor with gaseous fluorine to produce uranium hexafluoride,  $\text{UF}_6$ 
  - $\text{UF}_4 + \text{F}_2 \implies \text{UF}_6$

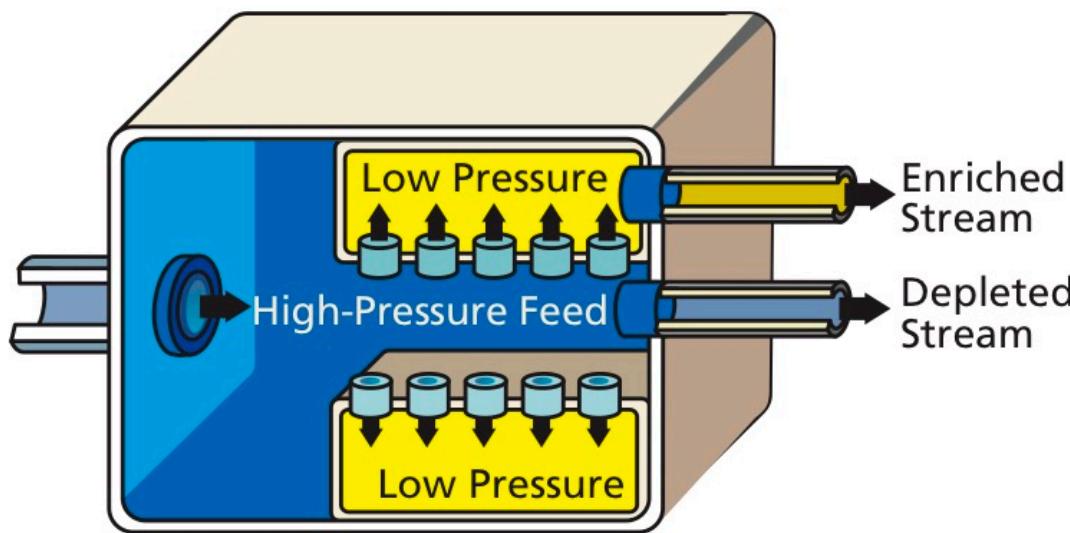
# Enrichment

- Natural uranium only contains 0.7% U-235, and therefore must be enriched to obtain suitable fissile material for fuel (for most reactors)
- The difference in mass between U-235 and U-238 allows the isotopes to be separated and makes it possible to enrich the percentage of U-235
- The capacity of enrichment plants is measured in terms of 'separative work units' or SWU
- Two main enrichment processes
  - Gaseous diffusion: 2500 kWh per SWU
  - Centrifuge: 50 kWh per SWU

# Enrichment

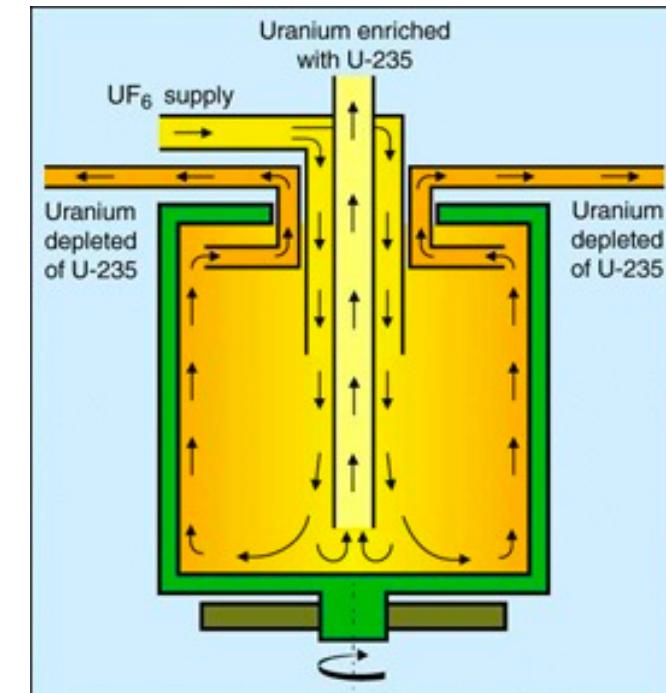
## – Gaseous diffusion

- Pushes UF<sub>6</sub> through porous membrane
- U<sub>235</sub>-F<sub>6</sub> travels slightly faster
- First Gen. technology, historical, but now outdated



## – Centrifuge

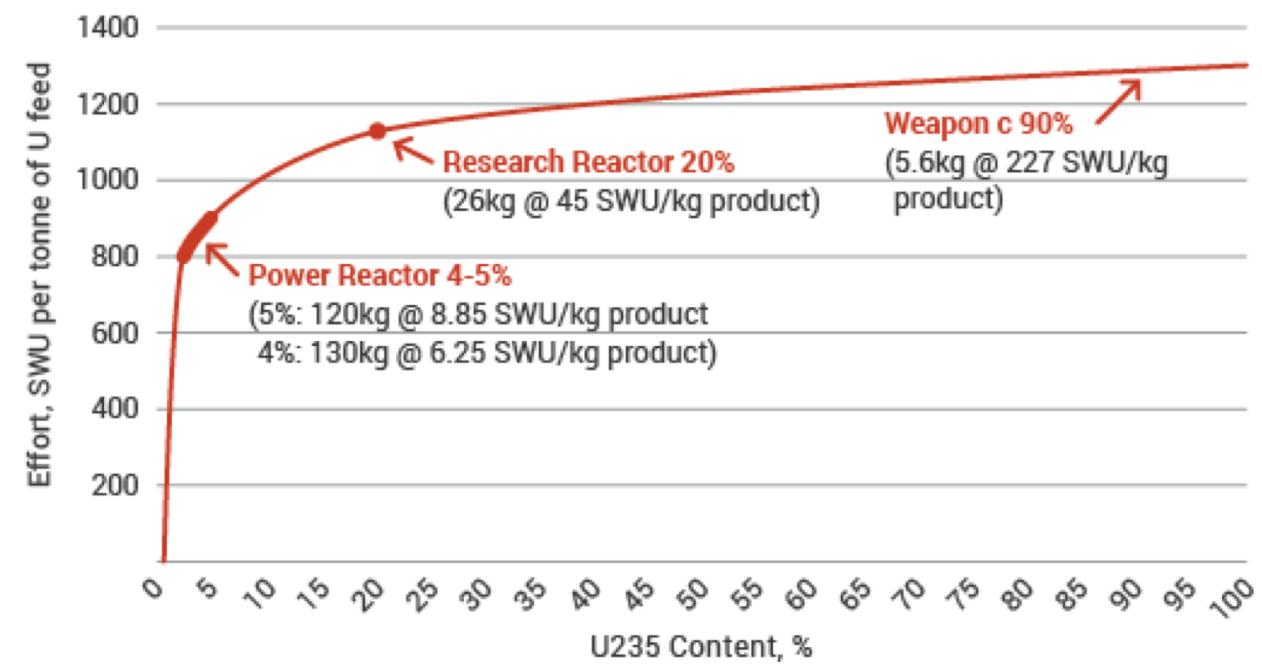
- gas is placed in a gas centrifuge cylinder and rotated at a high speed
- strong centrifugal force, heavier gas molecules move towards the outside of the cylinder



# Enrichment

- One ton of natural uranium feedstock might end up: as 120-130 kg of uranium for power reactor fuel, as 26 kg of typical research reactor fuel, or conceivably as 5.6 kg of weapons-grade material
- The curve flattens out so much because the mass of material being enriched progressively diminishes, so requires less effort relative to what has already been applied to progress a lot further in percentage enrichment

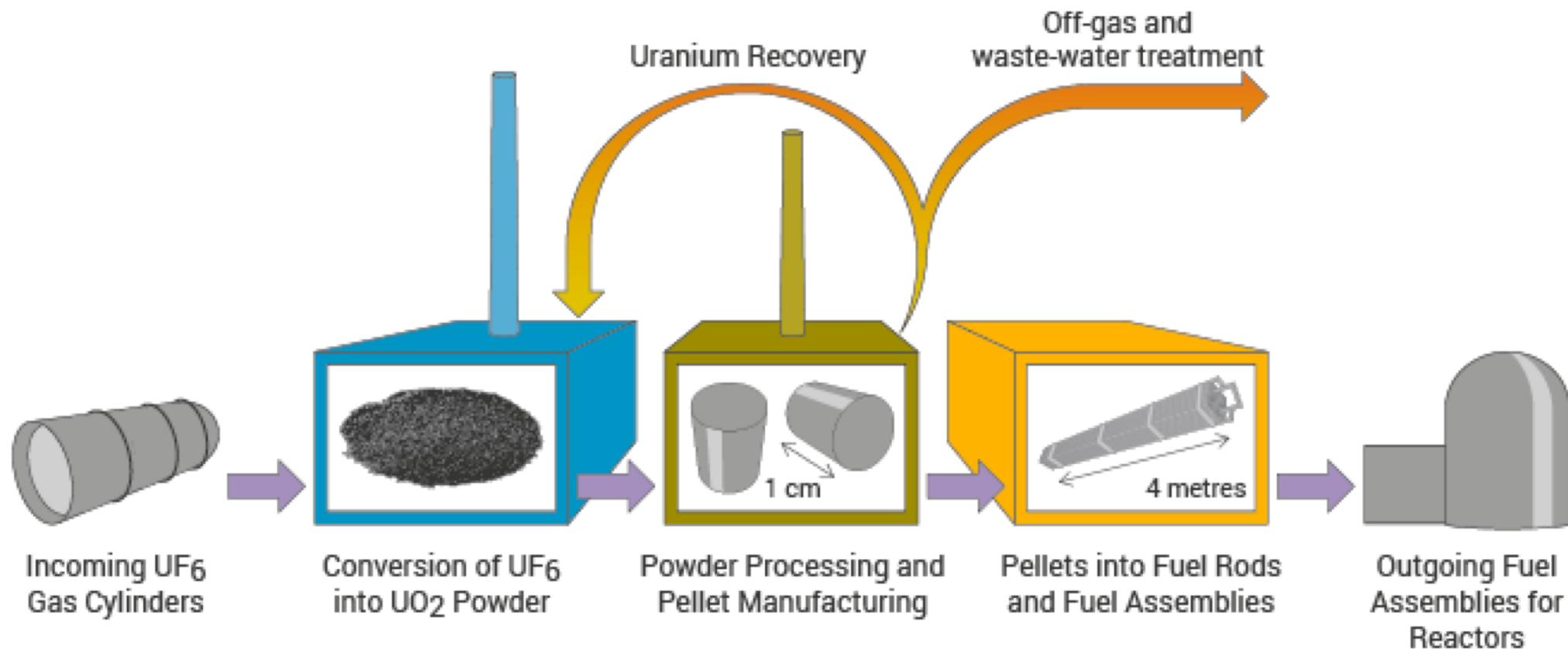
Uranium Enrichment and Uses



# Enrichment

- Enrichment accounts for almost half of the cost of nuclear fuel and about 5% of the total cost of the electricity generated
- It is also the main greenhouse gas impact from the nuclear fuel cycle where the electricity used for enrichment is typically generated from coal or natural gas
- However, it still only amounts to 0.1% of the carbon dioxide from equivalent coal-fired electricity generation if modern gas centrifuge plants are used

# Fabrication Process



# Powder Processing

- Uranium typically arrives at a fuel manufacturing plant as uranium hexafluoride ( $\text{UF}_6$ ) and needs to be converted to uranium dioxide ( $\text{UO}_2$ ) prior to pellet fabrication
- An example conversion process injects  $\text{UF}_6$  into water to form a  $\text{UO}_2\text{F}_2$  particulate slurry, ammonia ( $\text{NH}_3$ ) is added to this mixture and the  $\text{UO}_2\text{F}_2$  reacts to produce ammonium diuranate (ADU,  $(\text{NH}_3)_2\text{U}_2\text{O}_7$ ), after which the slurry is filtered, dried and heated in a reducing atmosphere to pure  $\text{UO}_2$ 
  - A reducing atmosphere is one in which oxidation is prevented by removal of oxygen and other oxidizing gases, and which may contain actively reducing gases such as hydrogen

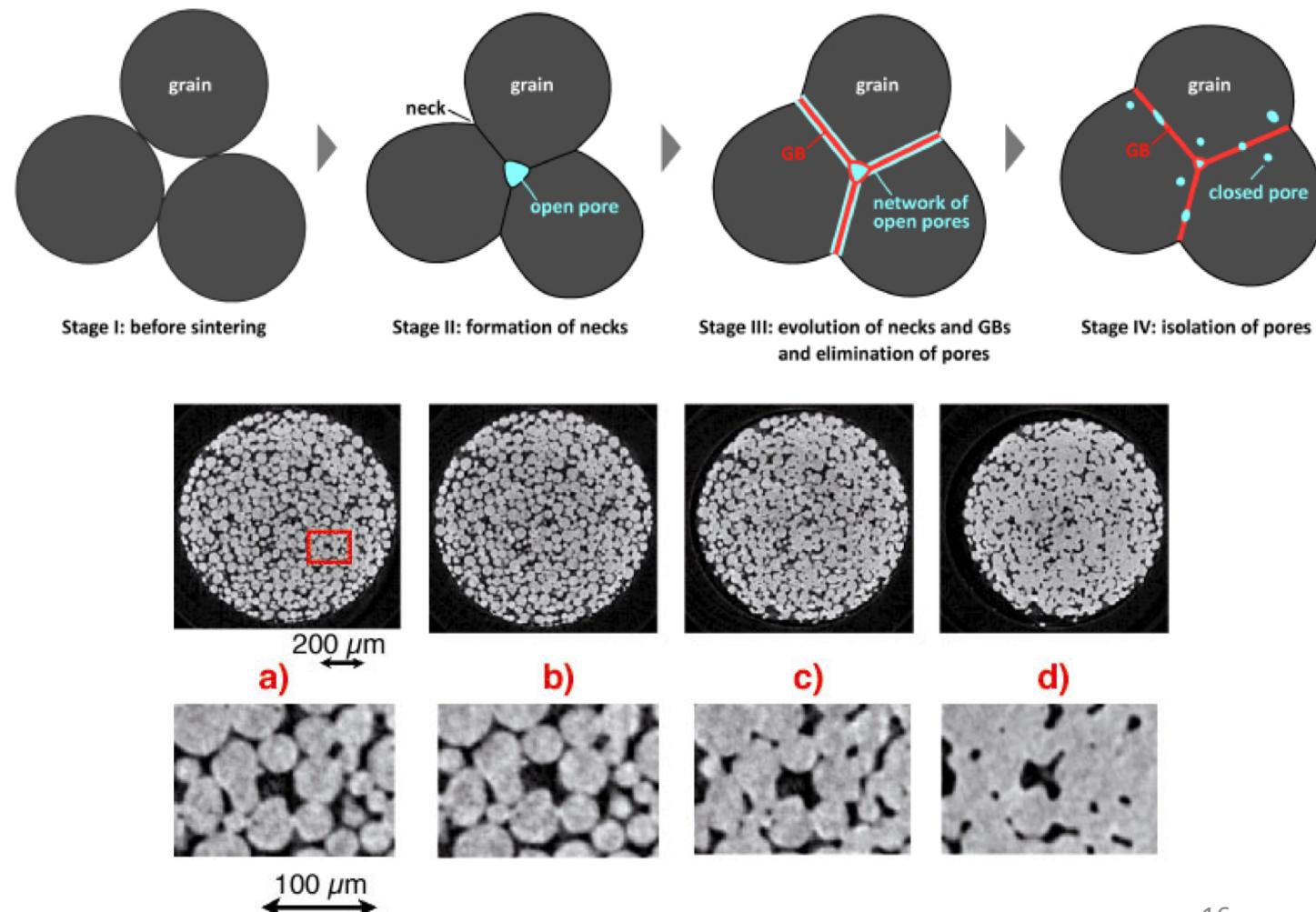


# Powder/Pellet Processing

- The  $\text{UO}_2$  powder may need further processing or conditioning before it can be formed into pellets:
  - Homogenization: powders may need to be blended to ensure uniformity in terms of particle size distribution and specific surface area
  - Additives:  $\text{U}_3\text{O}_8$  may be added to ensure satisfactory microstructure and density for the pellets and other fuel ingredients, such as lubricants, burnable absorbers (e.g. gadolinium) and pore-formers may also need to be added
- $\text{UO}_2$  powder is fed into dies and pressed biaxially into cylindrical pellet form using a load of several hundred MPa
- Pellets are then sintered in a heating furnace
  - Sintering is the process of compacting and forming a solid mass of material by heat or pressure

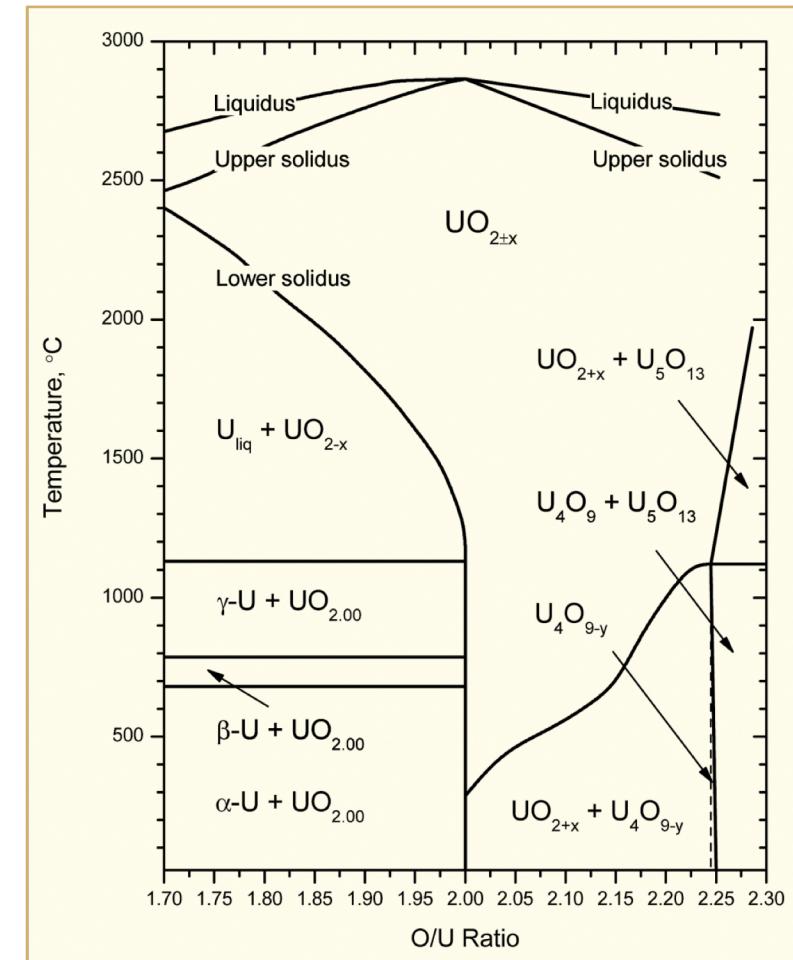
# Sintering Process

- During sintering, atoms in the materials diffuse across the boundaries of the particles, fusing the particles together and creating one solid piece
- The final fuel pellets are nearly fully dense with a uniform microstructure: grain size  $\sim 10 \mu\text{m}$ ; pore size  $\sim 3 \mu\text{m}$ ; density  $\sim 95 - 99\%$
- A single pellet in a typical reactor yields about the same amount of energy as one ton of coal



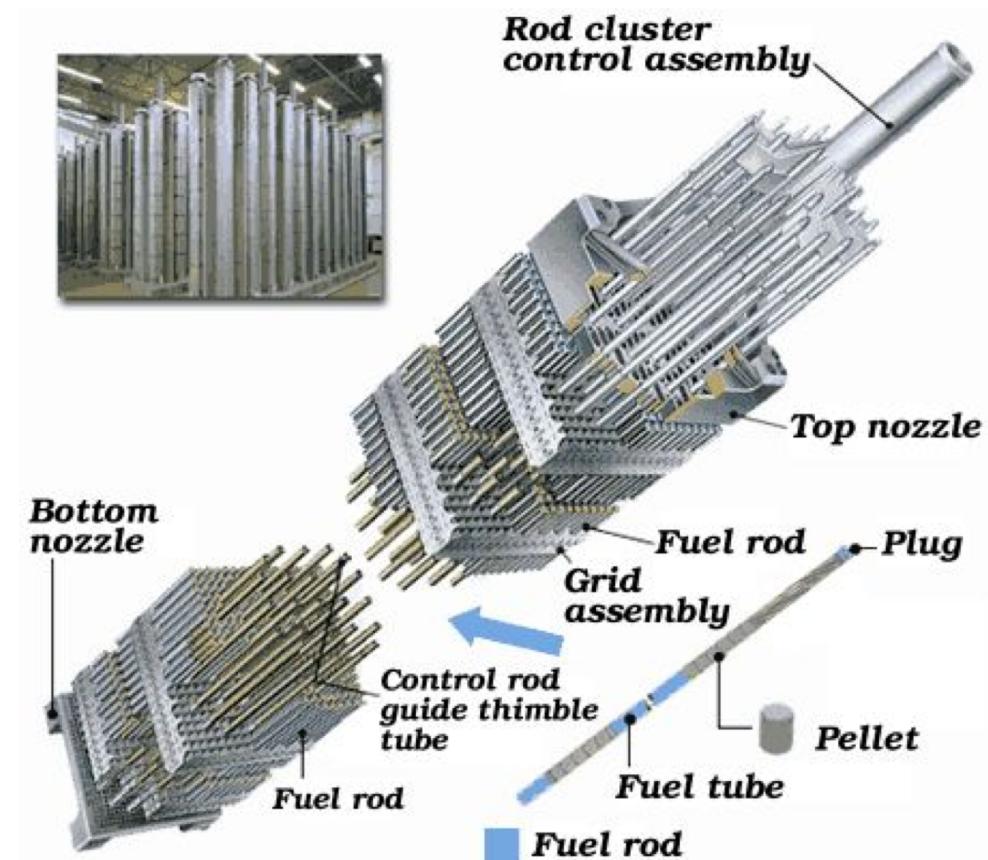
# Fuel strictly manufactured to be $\text{UO}_2$

- Fuel fabricated to be nearly stoichiometric; i.e.,  $\text{UO}_{2.00 \pm}$ 
  - Structure stable to  $T_{\text{melt}}$
  - Maximum  $T_{\text{melt}}$
- O/M ratio varies slightly during irradiation
- Large deviations from stoichiometry relevant to
  - Fabrication
  - Defected fuel behavior
  - Reprocessing
  - Accident conditions during dry storage or shipment of used nuclear fuel



# Rods and Assemblies

- The fuel pellets are assembled in fuel rods and then put together in fuel assemblies
- Designs dictate that the pellet-filled rods have a precise physical arrangement in terms of their lattice pitch (spacing), and their relation to other features such as water (moderator) channels and control-rod channels
- Physical structures for holding the fuel rods are therefore engineered with extremely tight tolerances and are largely constructed of steel and zirconium alloys



# Global Fuel Fabrication

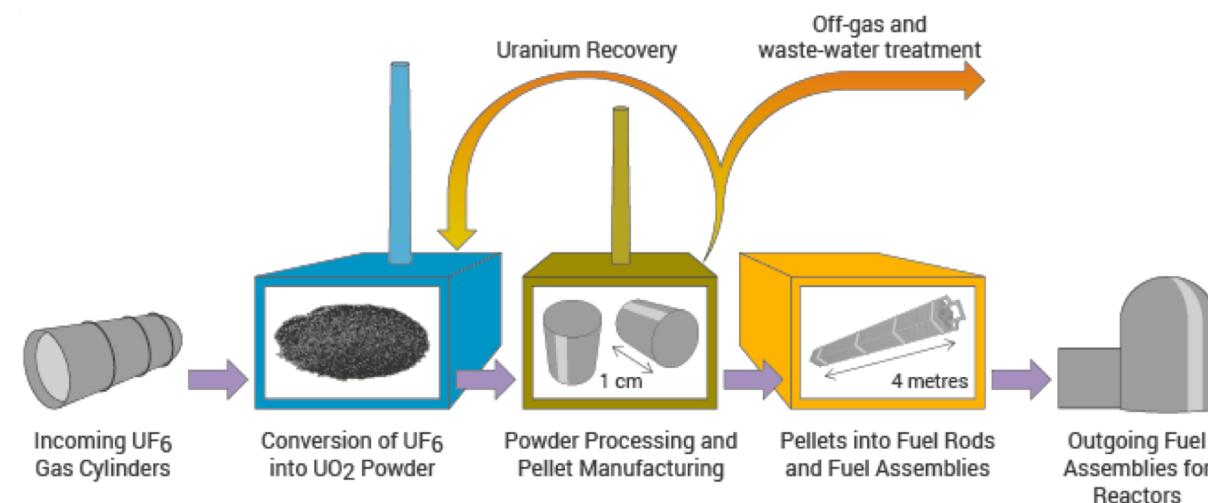
- Uranium is mined and converted into fuel in a number of countries
- USA, Russia, Kazakhstan and France are leaders
- There is a growing need for HALEU
  - High assay low enriched uranium
  - Uranium with 19.7% enrichment

Table 1: World LWR fuel fabrication capacity, tonnes/yr

	Fabricator	Location	Conversion	Pelletizing	Rod/assembly
Brazil	INB	Resende	160	160	240
China	CNNC	Yibin	400	400	450
		Baotou	200	200	200
France	AREVA NP-FBFC	Romans	1800	1400	1400
Germany	AREVA NP-ANF	Lingen	800	650	650
India	DAE Nuclear Fuel Complex	Hyderabad	48	48	48
	NFI (PWR)	Kumatori	0	360	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	450	440	440
Japan	Global NF-J	Kurihama	0	750	750
	Ulba	Ust Kamenogorsk	2000	2000	0
	KNFC	Daejeon	700	700	700
	TVEL-MSZ*	Elektrostal	1500	1500	1560
Russia	TVEL-NCCP	Novosibirsk	450	1200	1200
	ENUSA	Juzbado	0	500	500
Sweden	Westinghouse AB	Västeras	600	600	600
UK	Westinghouse**	Springfields	950	600	860
	AREVA Inc	Richland	1200	1200	1200
	Global NF-A	Wilmington	1200	1000	1000
USA	Westinghouse	Columbia	1500	1500	1500
	Total		13958	15418	13832 <sup>19</sup>

# Fuel Fabrication Summary

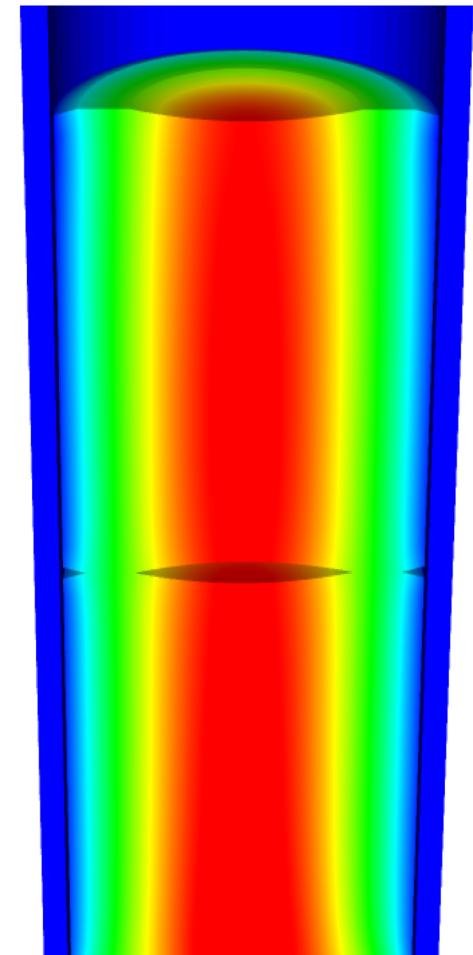
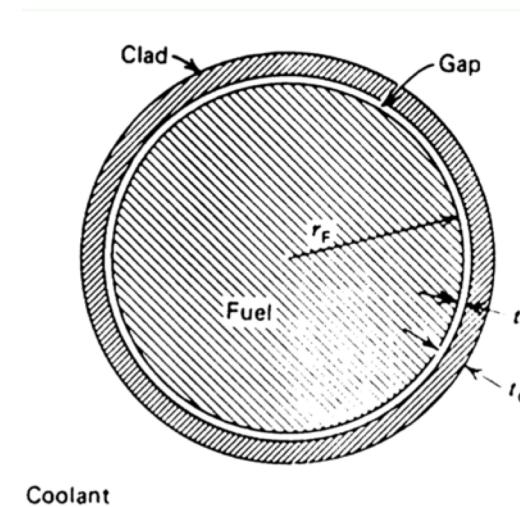
- Mining -> Processing -> Conversion -> Enrichment -> Powder -> Compaction/Sintering -> Rod/Assembly
- $\text{U}_3\text{O}_8$  must be converted to  $\text{UF}_6$  for enrichment, which is then converted to  $\text{UO}_2$  powder for pellet manufacture
- For different fuel types, enriched  $\text{UF}_6$  follows a different path



# HEAT TRANSPORT

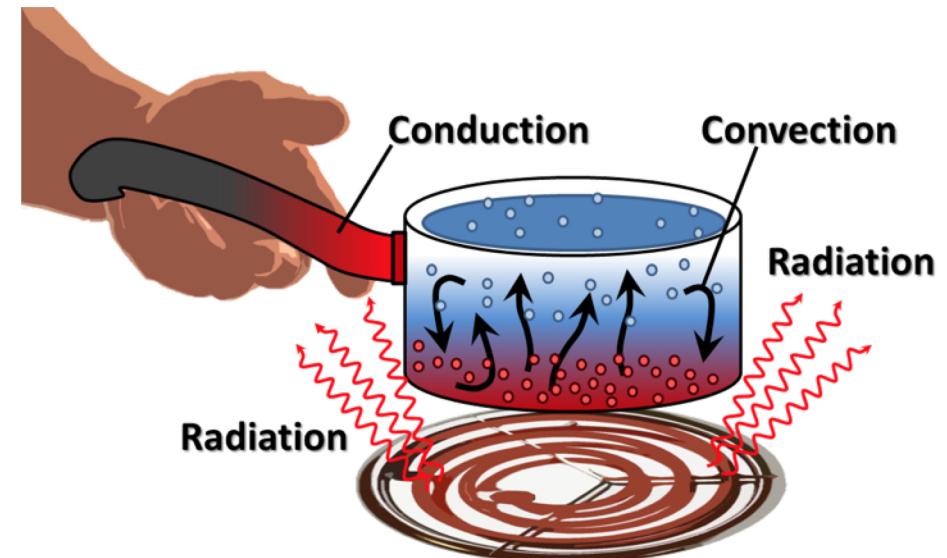
# Heat transport route

- Heat is produced in the fuel, transports through the cladding and gap, and into the coolant
- Important quantities include
  - Volumetric heat generation rate  $Q$  ( $\text{W/cm}^3$ )
  - Fuel Centerline temperature  $T_0$
  - Surface temperature of the fuel  $T_F$
  - Inner cladding temperature  $T_{Cl}$
  - Outer cladding temperature  $T_{Co}$
  - Coolant temperature  $T_{cool}$
  - Fuel pellet radius  $r_F$
  - Gap thickness  $t_G$
  - Cladding thickness  $t_c$



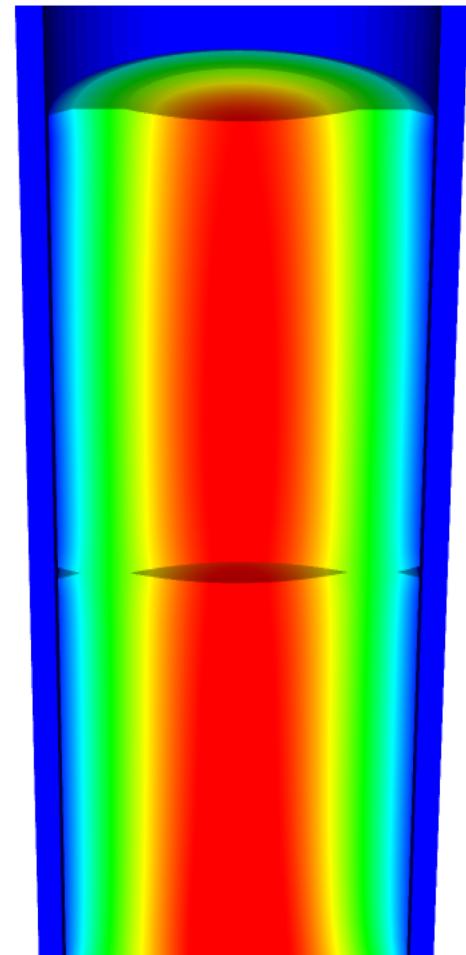
# Heat can be transported in three ways

- Convection
  - Heat transfer through mass movement of liquid or gas
- Radiation
  - Heat transfer by means of photons in electromagnetic waves
- Conduction
  - Heat transfer by molecular or atomic motion



# Heat transfer mode in fuel systems?

- How is heat transported through the fuel?  
**Conduction**
- How is the heat transported through the gap?  
**Mostly conduction, some convection**
- How is heat transported through the cladding?  
**Conduction**
- How is heat transported to the coolant?  
**Convection**



# Heat conduction equation

- $\rho$  is the density,  $c_p$  is the specific heat,  $T$  is the temperature,  $t$  is the time, and  $k$  is the thermal conductivity
- It is a partial differential equation in time and space
- We are solving for the  $T$  as a function of space and time
  - $T(\mathbf{x}, t)$ , where  $\mathbf{x}$  is a vector defining the position in space
- What do we need to know to solve this equation?

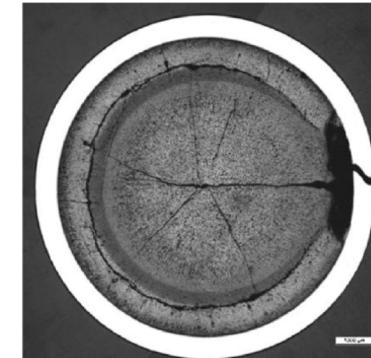
$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T)$$

- The geometry of our problem
- The initial condition of  $T$
- The boundary conditions of  $T$
- Is each parameter is a function of  $T$
- If they aren't a function of  $T$ , do they vary in space and time for some other reason?

# What is our geometry for the problem?

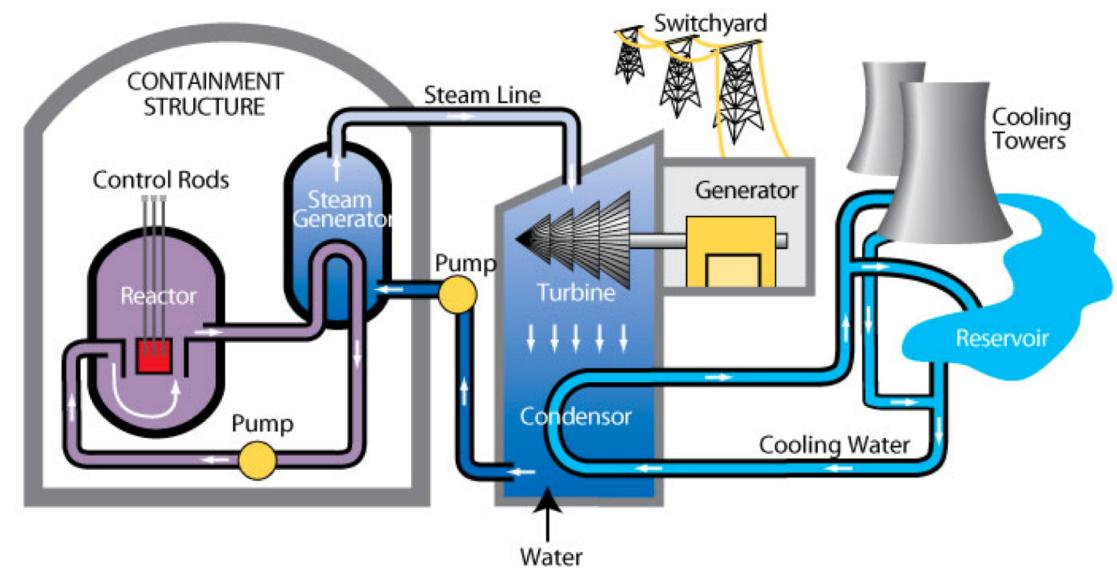
- Reactor geometry depends on reactor type
- The ideal geometry of each fuel rod is axisymmetric, but in reality it is 3D
- Fuel pellet defects cause 3D geometry
- The stacked pellets may not be stacked perfectly, causing their center axis to not be aligned, also causing 3D geometry

BWR		PWR	
Lattice	10x10	14x14 – 18x18	
Lattice size	~5.3"	~9"	
Height	120"-150"	144"-168"	
Fuel	UO <sub>2</sub> /MOx	UO <sub>2</sub> /MOx	
Fuel rods	~92	176-300	
Part length rods	~14	0	
Non-fueled rods	~2	20-25	
Control	Ext. control rod	Int. control cluster	
Cladding	Zr2	Zr4/Zirlo/M5	
for PCI, nodular corrosion		for uniform corrosion & hydrogen	
Channels	Yes	No	
Fuel mass	~180 kgU	~600 kgU	



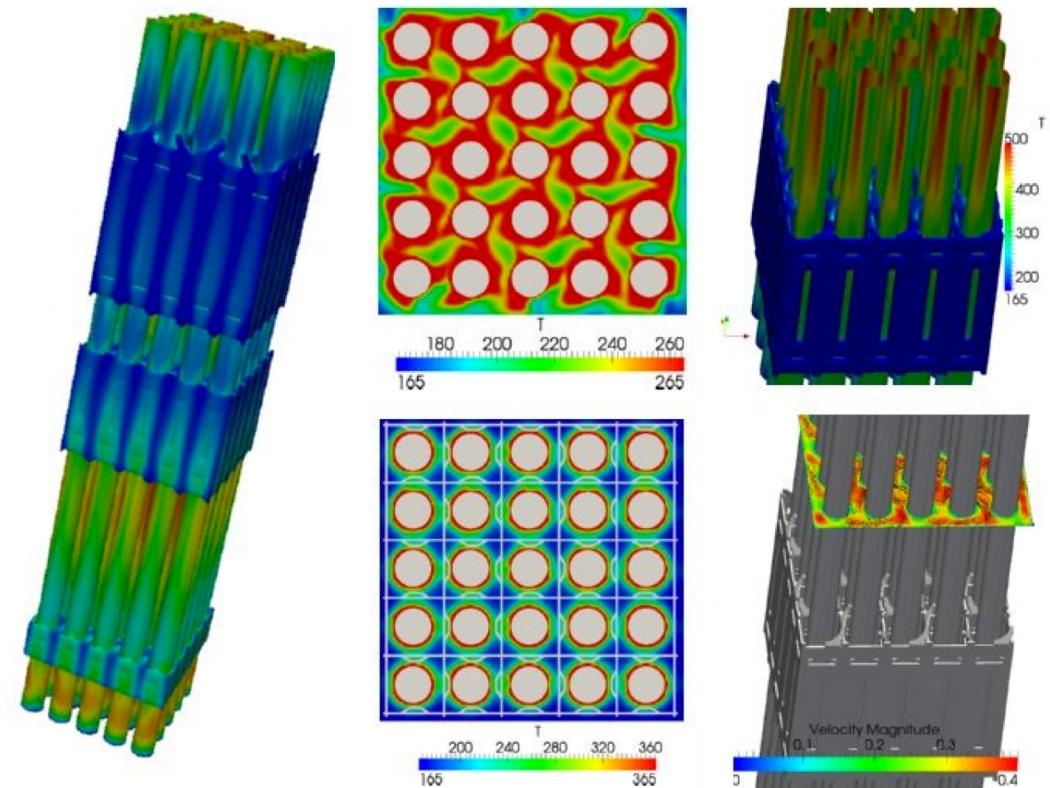
# The initial condition of T

- The initial condition of T is set by the state of the reactor directly before startup
- What is the initial temperature profile of the fuel?
- The initial temperature is uniform throughout the fuel
- It is equal to the initial coolant temperature
- $T(x, 0) = T_{cool}(0)$



# Boundary conditions?

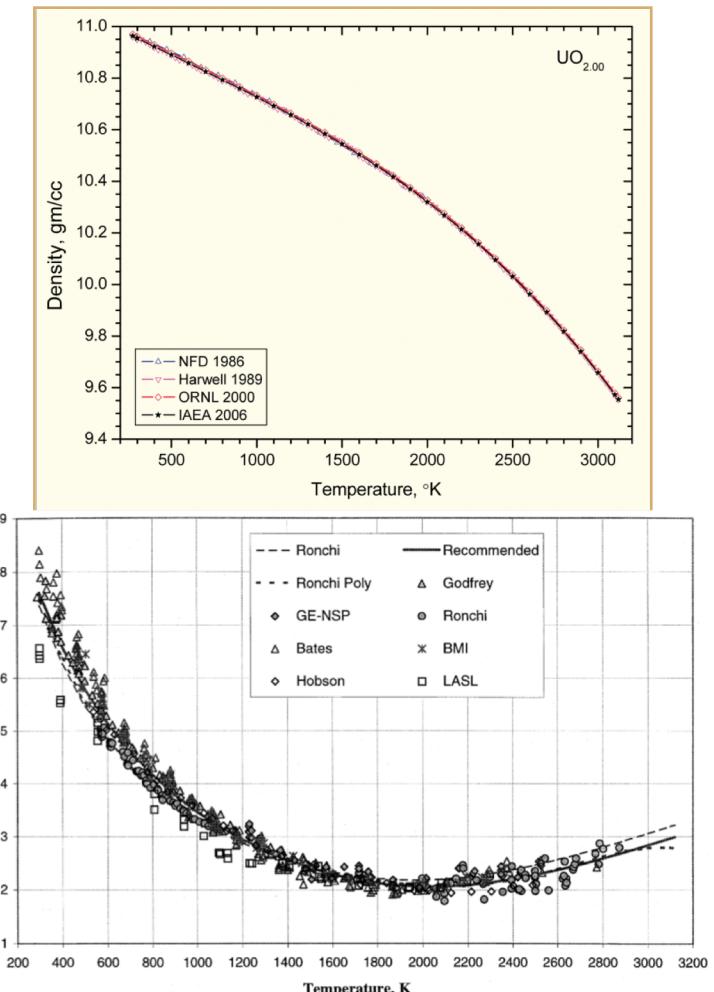
- The boundary conditions on  $T$  is set by the coolant flow
- The temperature of the coolant  $T_{cool}$  is complicated
  - It varies along the length of the fuel rod (axially)
  - It varies around the circumference of the fuel rod



# Fuel properties

- Density varies as a function of T (thermal expansion)
  - Also varies as a function of composition (thus as a function of burnup/time)
- Thermal conductivity also varies with temperature

$$k_0 = \frac{100}{7.5408_{17.629t} + 3.6142t^2} + \frac{6400}{t^{5/2}} \exp\left(\frac{-16.35}{t}\right)$$



# The heat capacity is a function of temperature

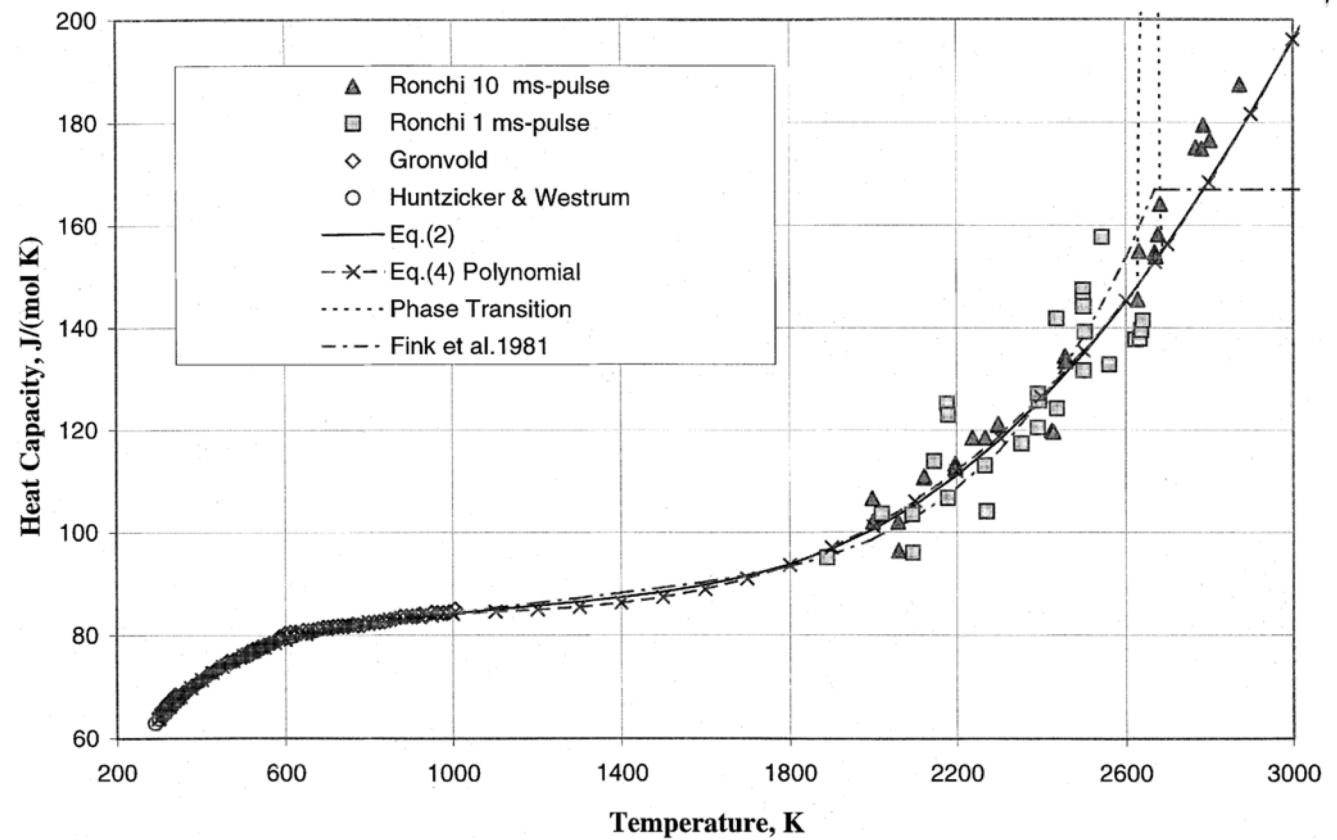
$$C_P = \frac{C_1 \theta^2 e^{\theta/T}}{T^2(e^{\theta/T} - 1)^2} + 2C_2 T + \frac{C_3 E_a e^{-E_a/T}}{T^2}$$

$$\theta = 548.68,$$

$$C_2 = 2.285 \times 10^{-3}$$

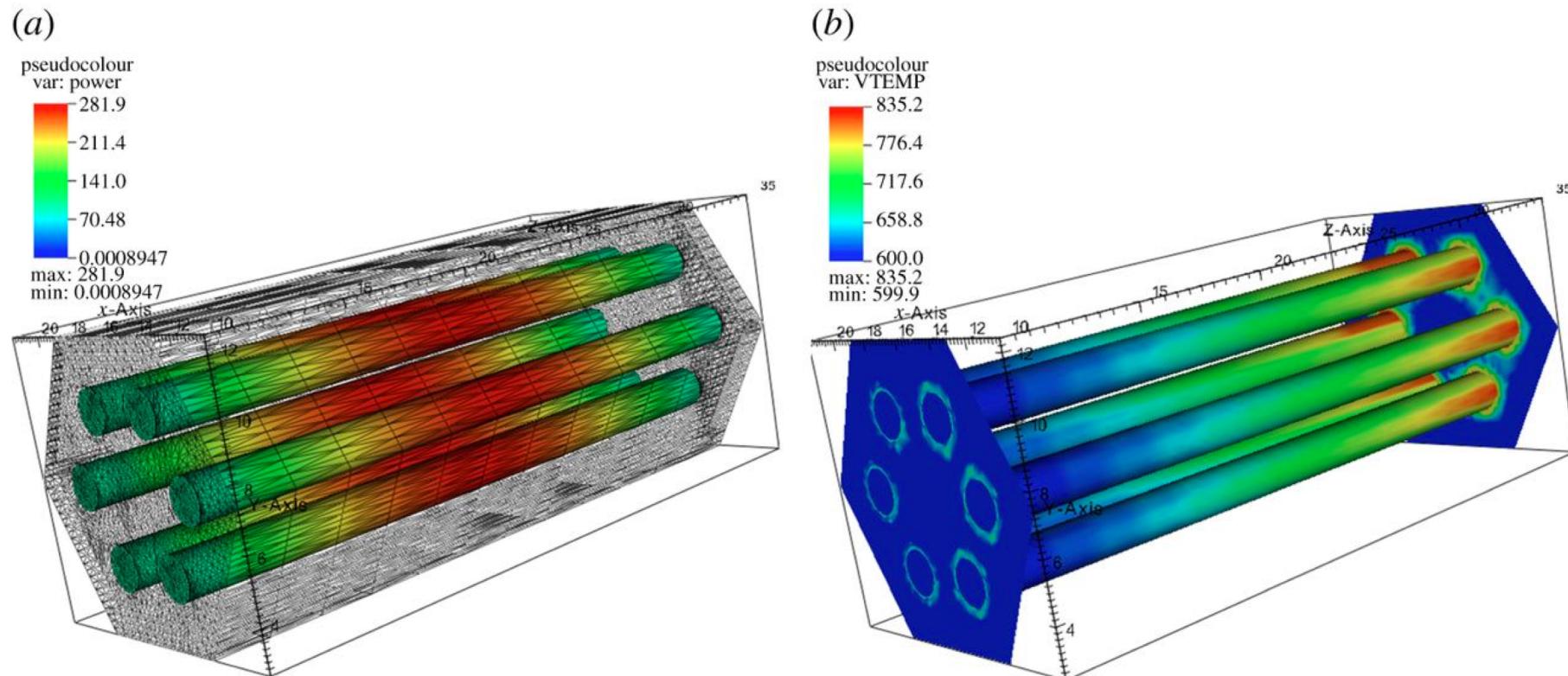
$$C_3 = 2.360 \times 10^7$$

$$E_a = 18531.7$$



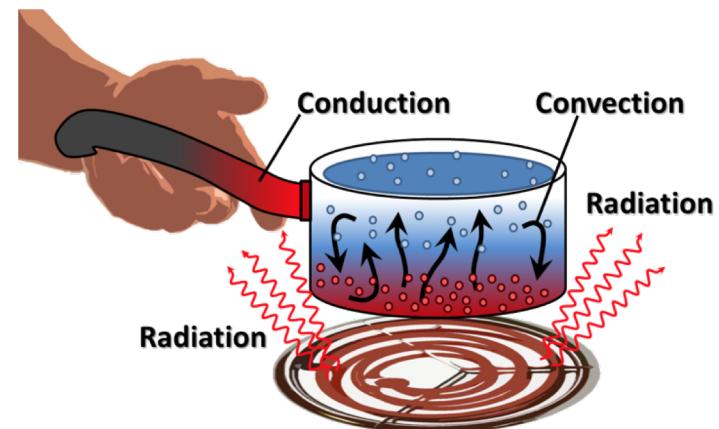
# The heat generation rate is a function of the thermal neutron flux, which varies in time and space

$$Q = E_f N_f \sigma_f \varphi_{\text{th}}$$



# Summary

- General heat transport
- Heat is produced in the fuel, transports through the cladding and gap, and into the coolant
- The geometry of our problem
- The initial condition of T
- The boundary conditions of T
- Is each parameter is a function of T
  - Thermal conductivity, heat capacity
- Function of space/time?
  - Heat generation, dependent upon flux



$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T)$$