PennState College of Engineering

NucE 497: Reactor Fuel Performance

Lecture 5: Reactor fuel fabrication

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Mechanical and Nuclear Engineering

Today we will learn how go from mined uranium to enriched LWR fuel pellets

- Module 1: Fuel basics
  - Purpose of the fuel and types of fuel
  - Fission, heat generation, fission products
  - Reactor requirements, 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

Fuel pellets are manufactured in high volume

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
Japan	NFI (PWR)	Kumatori	0	360	284
	NFI (BWR)	Tokai-Mura	0	250	250
	Mitsubishi Nuclear Fuel	Tokai-Mura	450	440	440
	Global NF-J	Kurihama	0	750	750
Kazakhstan	Ulba	Ust Kamenogorsk	2000	2000	0
Korea	KNFC	Daejeon	700	700	700
Russia	TVEL-MSZ*	Elektrostal	1500	1500	1560
	TVEL-NCCP	Novosibirsk	450	1200	1200
Spain	ENUSA	Juzbado	0	500	500
Sweden	Westinghouse AB	Västeras	600	600	600
UK	Westinghouse**	Springfields	950	600	860
USA	AREVA Inc	Richland	1200	1200	1200
	Global NF-A	Wilmington	1200	1000	1000
	Westinghouse	Columbia	1500	1500	1500
Total			13958	15418	13832

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/fuel-fabrication.aspx

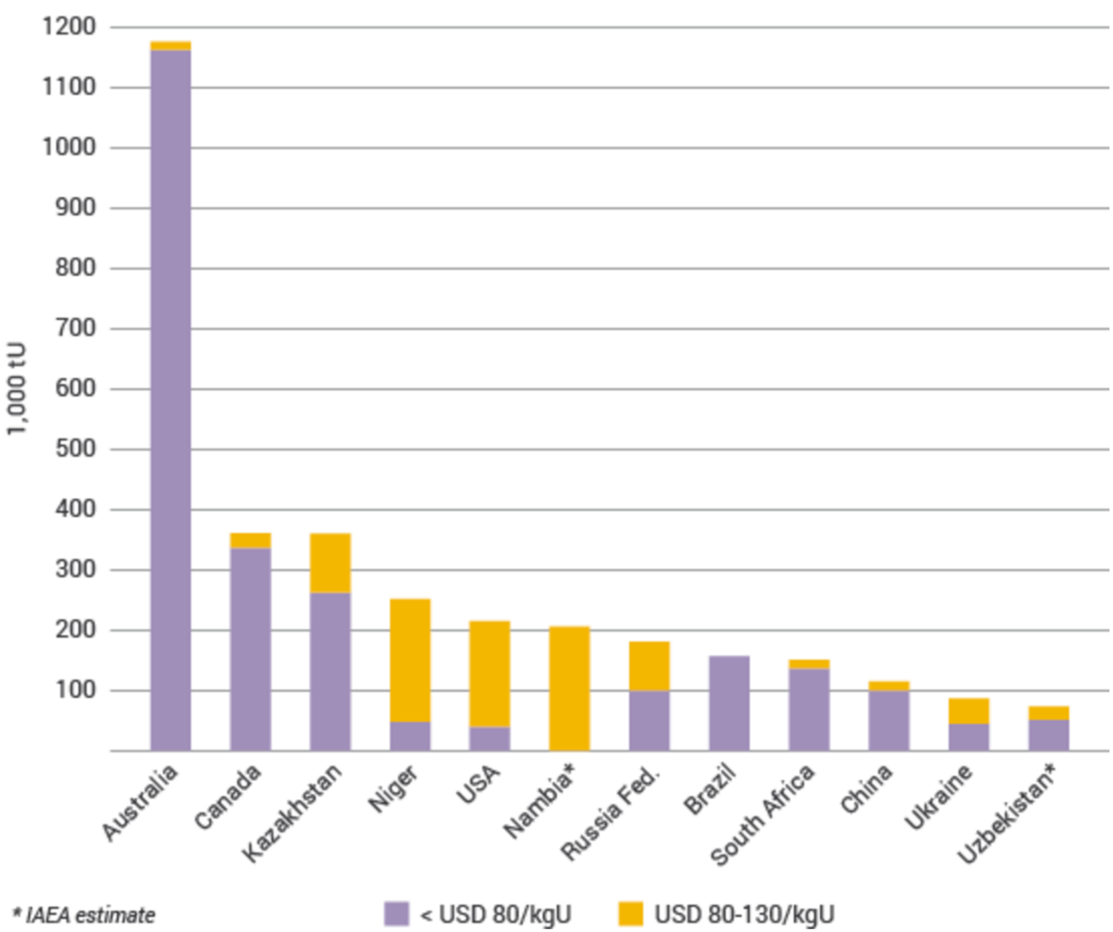
It takes several steps to get from uranium in the ground to a LWR fuel assembly

1. Mining
2. Milling
3. Conversion
4. Enrichment
5. Fuel fabrication

Nuclear Fuel Cycle

Uranium is a relatively common element in the crust of the Earth, approximately as common as tin or zinc

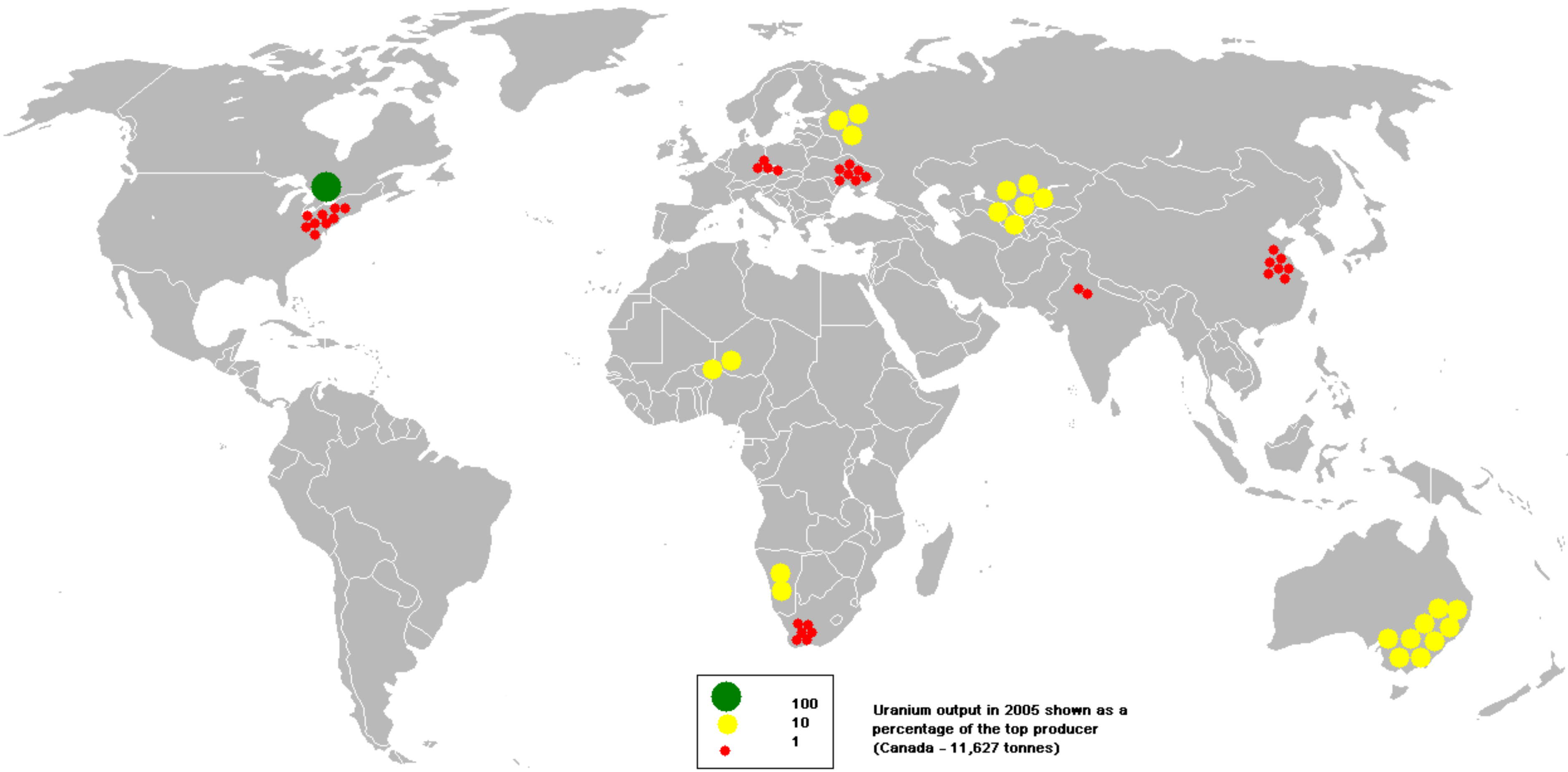
Reasonably Assured Resources of Uranium in 2009



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%
World total	5,718,400	

Uranium is mined all across the world

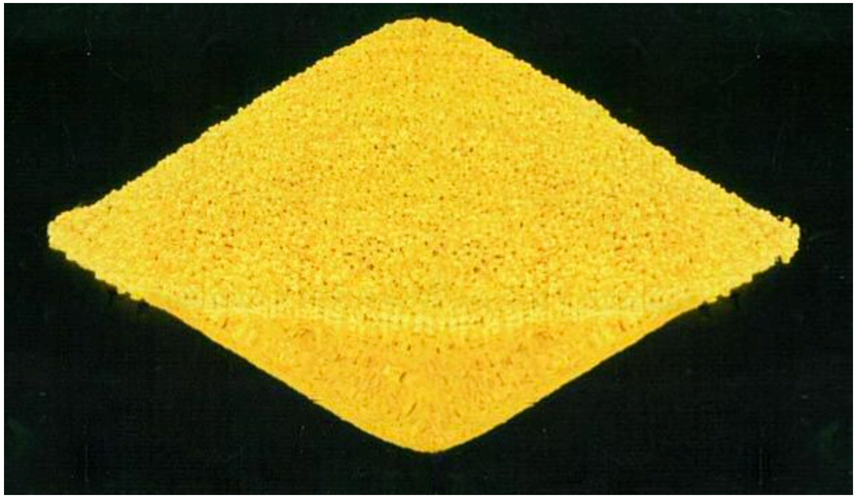


Uranium is found as UO_2 or U_3O_8 in a number of different geological environments

- Most Kazakh uranium resources are sedimentary.
- Most Canadian resources are unconformity-related.
- Most Australian uranium resources are in unconformity-related and iron oxide breccia complex orebodies

Mined UO_2 is then milled to form Yellowcake

- The ore is crushed to a fine powder by passing raw uranium ore through crushers and grinders
- This is further processed with concentrated acid, alkaline, or peroxide solutions to leach out the uranium.
- Yellowcake is what remains after drying and filtering.
- Modern yellowcake is brown or black, not yellow
- Yellowcake is 70% to 90% U_3O_8. It also has UO_2 and UO_3.



The first step in enrichment is conversion to UF_6

- Yellowcake has 0.7% U-235. It needs to be enriched to 3% to 5%.
- The first step in enrichment is to convert U_3O_8 to UO_2 in a kiln
  - $U_3O_8 + 2H_2 \text{ ===> } 3UO_2 + 2H_2O$, $\Delta H = -109$ kJ/mole
- The second step is conversion from UO_2 to UF_4 in a kiln
  - $UO_2 + 4HF \text{ ===> } UF_4 + 2H_2O$, $\Delta H = -176$ kJ/mole
- The last step is to convert UF_4 to UF_6
  - $UF_4 + F_2 \text{ ===> } UF_6$
- The uranium hexafloride is stored for enrichment. This form is required because it is gaseous at low temperature.

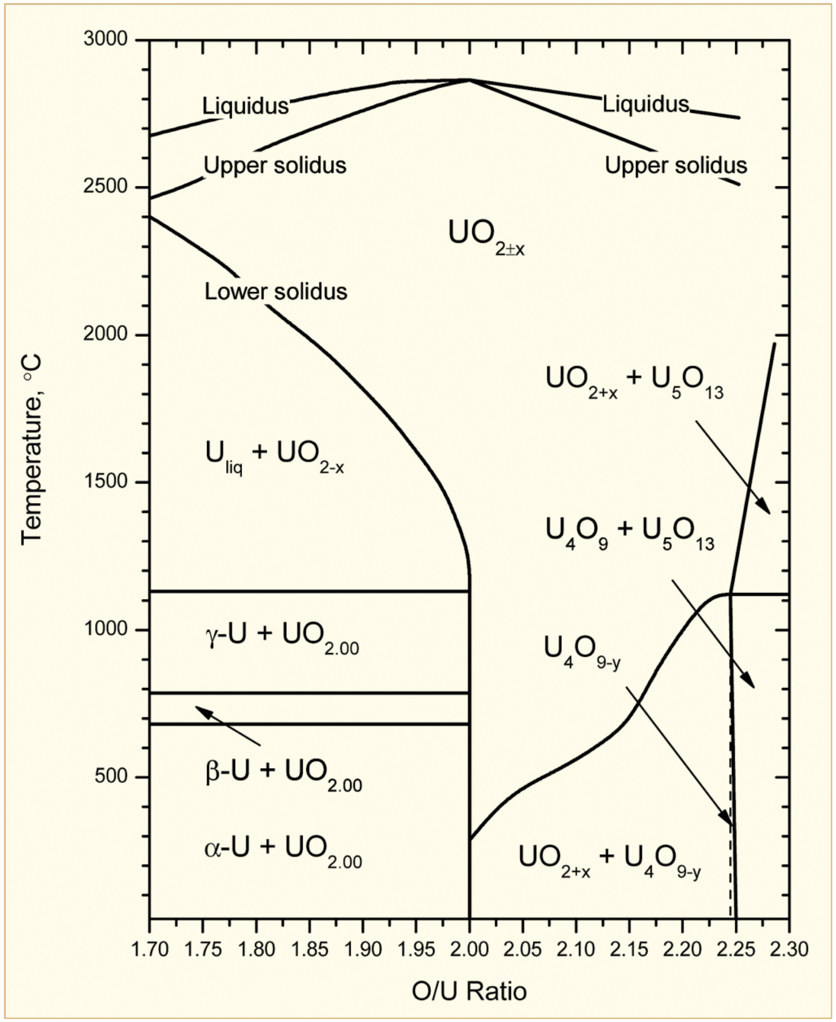
UF_6 is enriched by taking advantage of the difference in weight of U-235 and U-238

- Uranium can only be enriched in gas form
- Commonly, enrichment is done in centrifuges
- An Australian process based on laser excitation is under development
- Enrichment is a sensitive and is under tight international control

World enrichment capacity – operational and planned (thousand SWU/yr)

Country	Company and plant	2013	2015	2020
France	Areva, Georges Besse I & II	5500	7000	7500
Germany-Netherlands-UK	Urenco: Gronau, Germany; Almelo, Netherlands; Capenhurst, UK.	14,200	14,400	14,900
Japan	JNFL, Rokkaasho	75	75	75
USA	USEC, Piketon	0*	0	0
USA	Urenco, New Mexico	3500	4700	4700
USA	Areva, Idaho Falls	0	0	0
USA	Global Laser Enrichment, Paducah	0	0	0
Russia	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	26,000	26,578	28,663
China	CNNC, Hanzhun & Lanzhou	2200	5760	10,700+
Other	Various: Argentina, Brazil, India, Pakistan, Iran	75	100	170
	Total SWU/yr approx	51,550	58,600	66,700
	Requirements (*WNA reference scenario*)	49,154	47,285	57,456

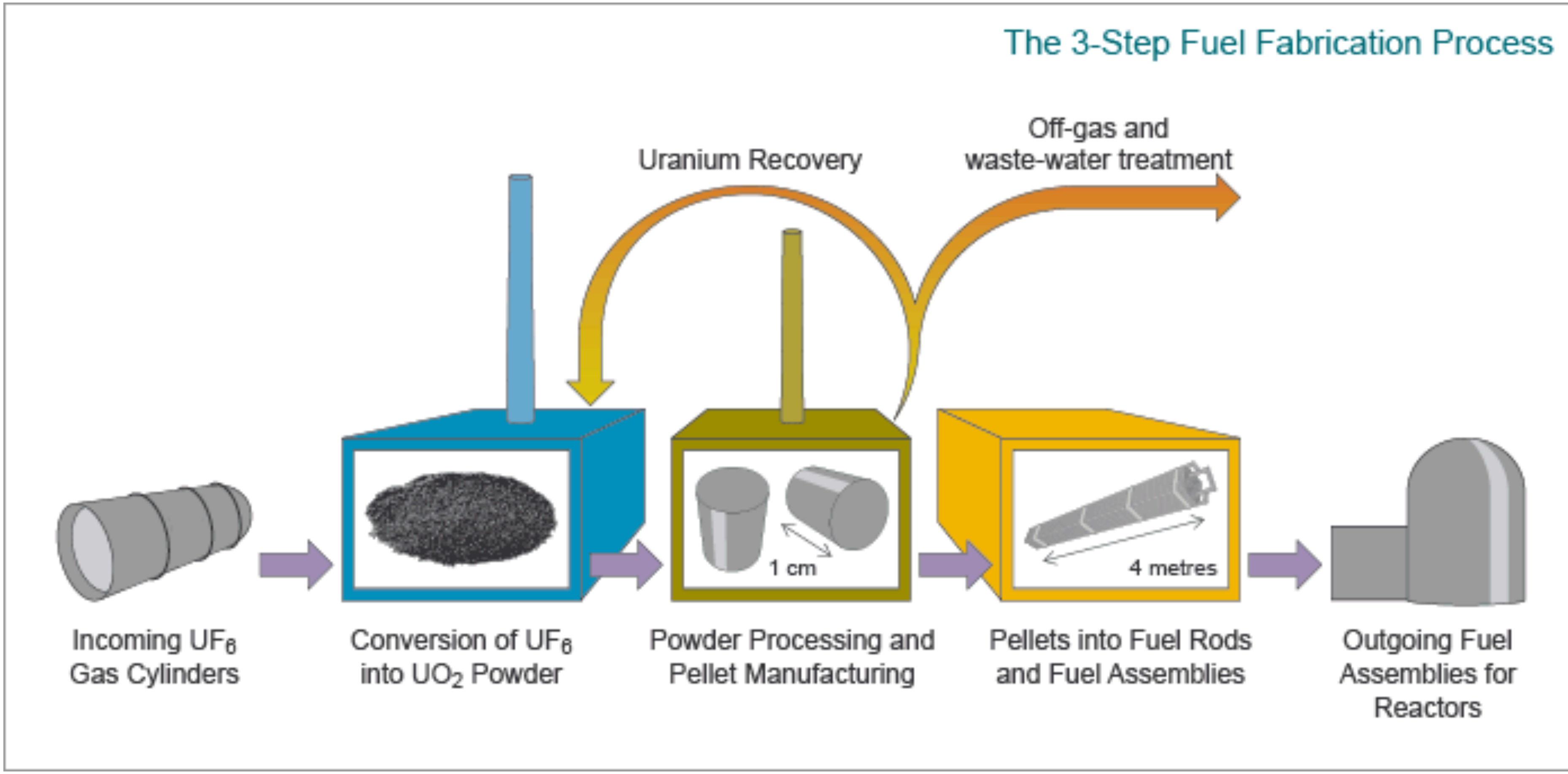
4. Fuel Chemistry



[Levin & McMurdie, 1975], [Olander, 1976], [Kim, 2000], [Guéneau et al, 2002], [Baichi et al, 2006], [Rudling et al, 2007]

- Fuel fabricated to be nearly stoichiometric; i.e., $UO_{2.00\pm}$
  - Structure stable to T_{melt}
  - Maximum T_{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

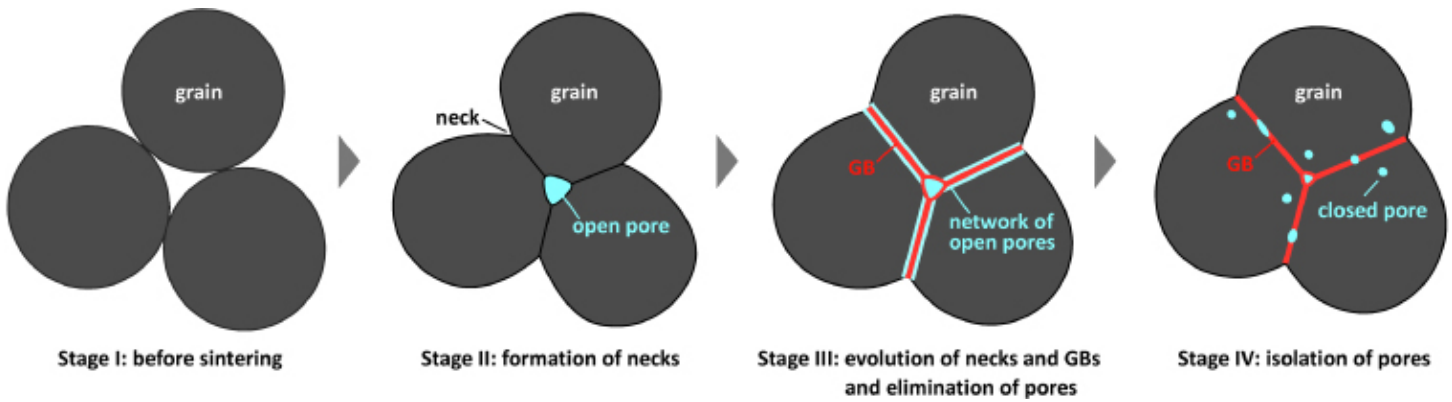
There are three main stages in the fabrication of the nuclear fuel structures used in LWRs

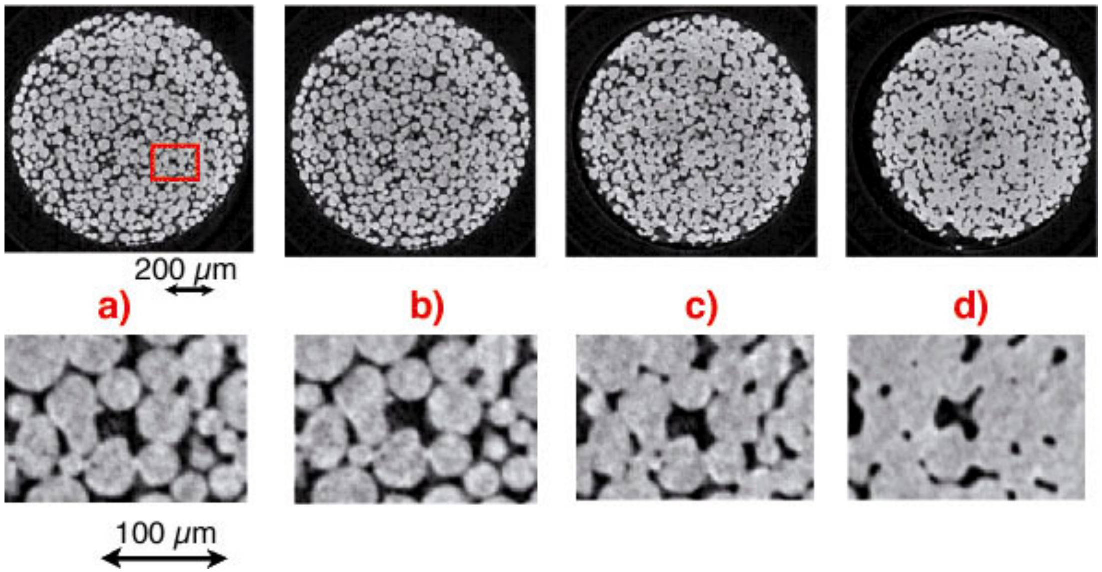


The enriched UF_6 gas must be converted back into UO_2 powder

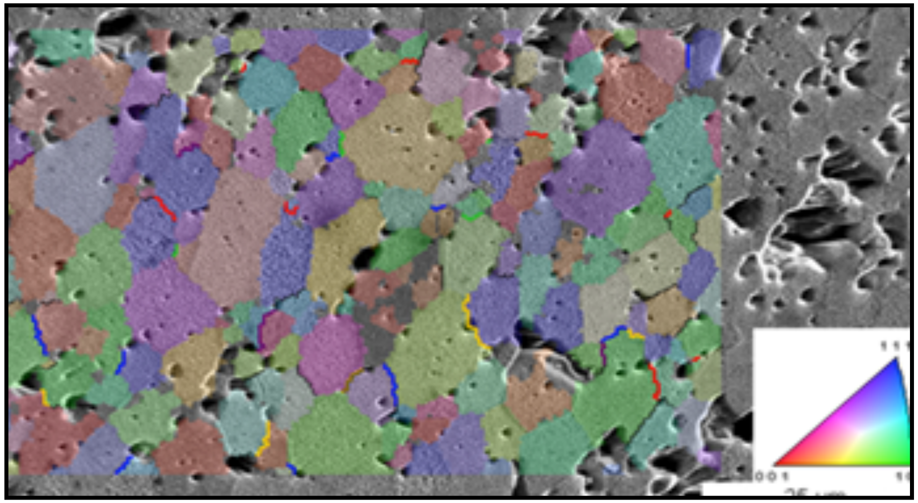
- One approach is dry (gaseous)
  - The first step is to create solid uranyl-floride by mixing UF_6 with steam
    - $UF_6 + 2H_2O \Longrightarrow UO_2F_2 + 4HF_3$
  - Then, it is reacted with hydrogen gas
    - $UO_2F_2 + H_2 \Longrightarrow UO_2 + 2HF$
- The other is wet (liquid)
  - UF_6 is injected into water to form a uranyl-floride particulate slurry.
    - $UF_6 + 2H_2O \Longrightarrow UO_2F_2 + 4HF_3$
  - Then, two possible reactions are used
    - $UO_2F_2 + NH_3 = (NH_3)2U_2O_7$
    - $UO_2F_2 + (NH_3)2CO_3 = UO_2\ CO_3\ (NH_3)2CO_3$
  - In both cases the slurry is filtered, dried and heated in a reducing atmosphere to pure UO_2.

The fuel pellets are created from the powder using sintering (under high temperature and pressure)





The final fuel pellets are nearly fully dense with a uniform microstructure



Fabrication:
- powder-compact, sintering

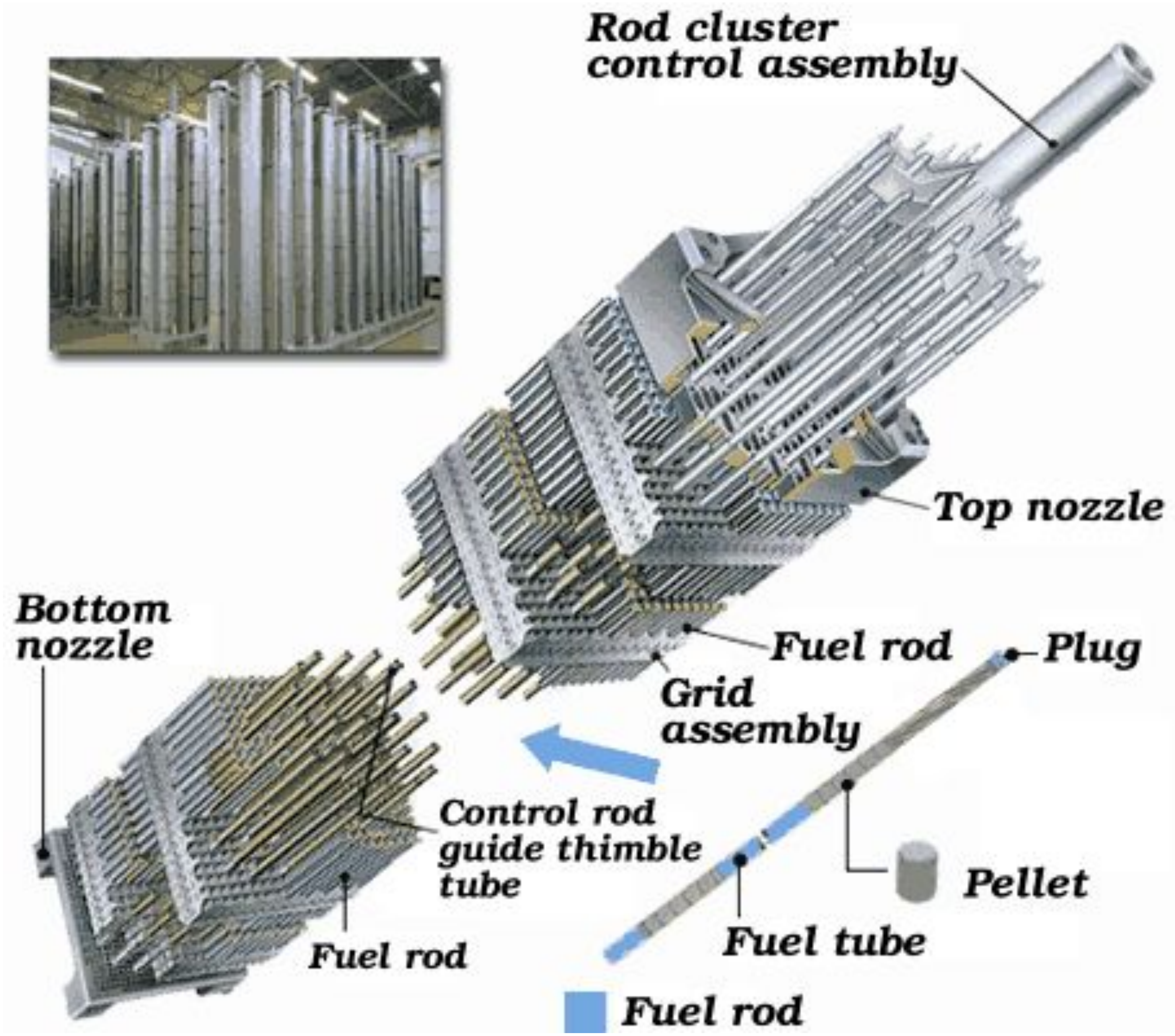
Dimensions:
- diameter (~ 1 cm)
- height (~ 1.2 cm)

Enrichment:
- 5% (U^{235}) (used to be 3%)

Microstructure
- Grain Size ≈ 10 μm
- Pore Size ≈ 3 μm
- Density ≈ 95 - 99%

Hodkin, JNM 88 (1980) 7.

The fuel pellets are assembled in fuel rods and then put together in fuel assemblies



Summary

- Fuel assemblies are created following these steps:
  1. Mining
  2. Milling
  3. Conversion
  4. Enrichment
  5. Fuel fabrication
- Fuel fabrication has three parts
  1. Deconversion from UF_6 to UO_2 powder
  2. Sintering of powder to form pellets
  3. Assembly of the fuel rods and fuel assemblies

Where can you work with a NucE degree?

Industry
- Plant operator
- Process engineer
- Reactor analyst

National Laboratory
- Staff scientists
- Staff techs

University
- Research scientists
- Faculty

What degree do you need for each job?

Industry

- Ph.D.
- M.S.
- B.S.

National Laboratory

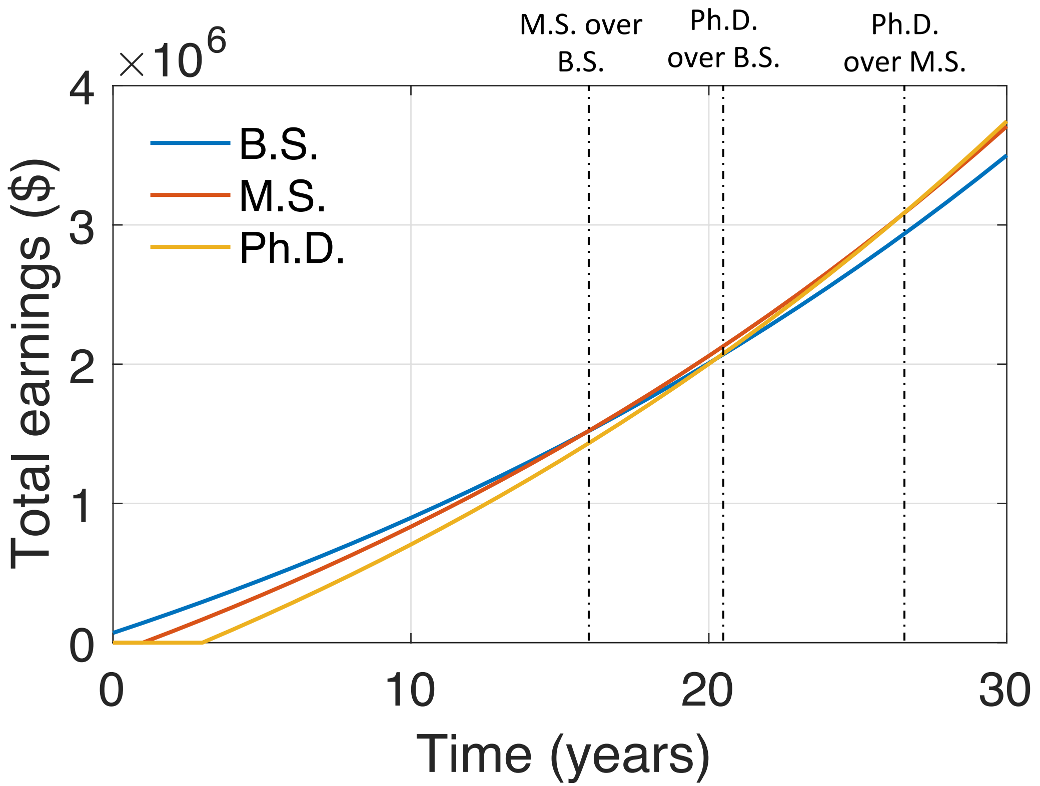
- Ph.D.
- M.S

University

- Ph.D.

Higher degrees don't pay off financially for many years

- Starting salary (very approximate):
  - B.S. - $70,000
  - M.S. - $82,000
  - Ph.D. - $92,000
- Plot assumes a 3% raise each year



There is a lot more to job satisfaction then just money

- With a B.S., you typically
  - Perform similar tasks you entire career
  - Spend your career as normal level engineer, technician, etc.
  - Your following orders, not giving ghem
- With an M.S., you
  - You design things, analyze things, come up with new ideas
  - You may be able to move into management, depending on the company
- With a Ph.D.
  - You will work in research and development
  - You have lots of freedom to do whatever you can come up with
  - You will definitely have chances to do management if you want them