Chemical Engineering 412

Introductory Nuclear Engineering

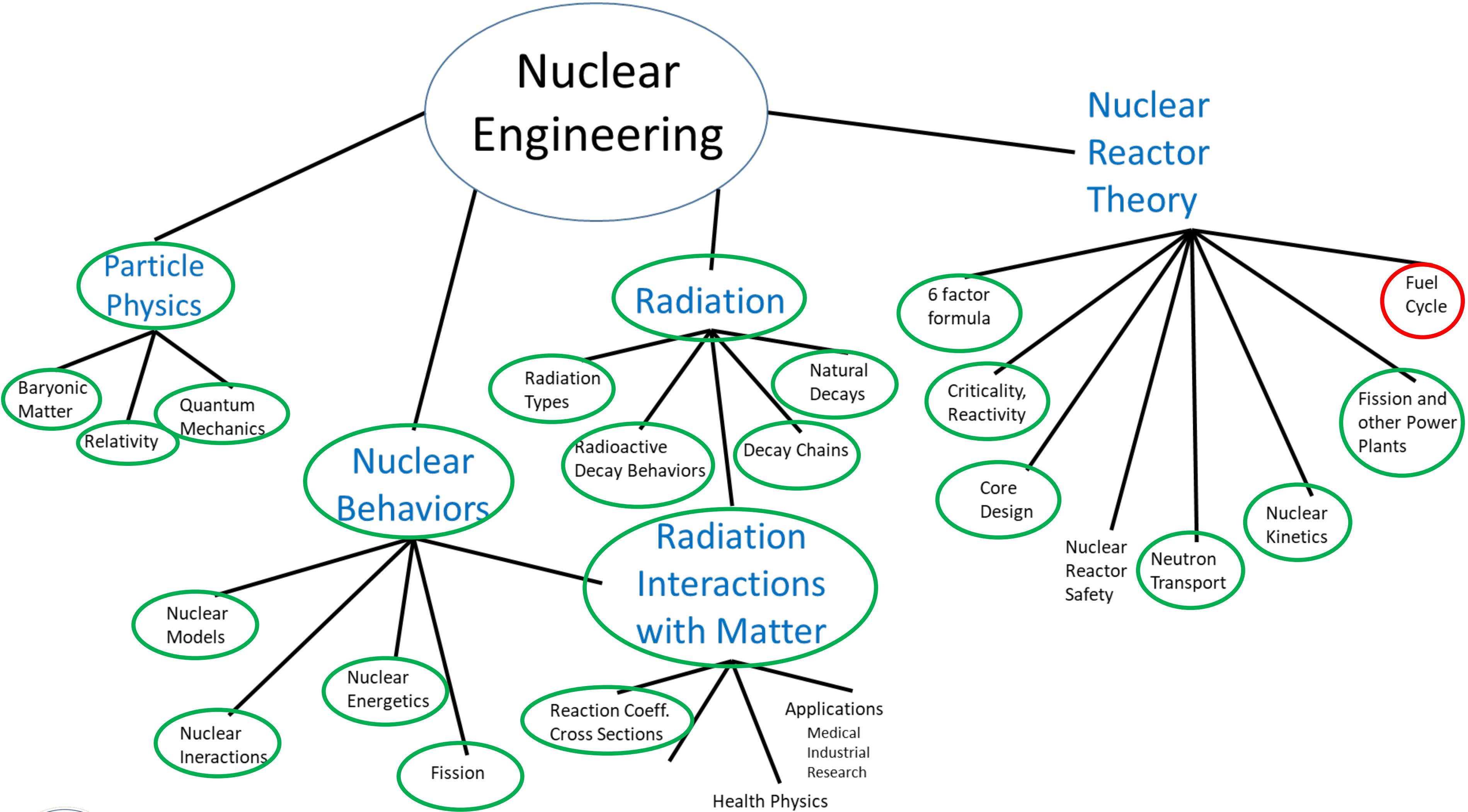
Lecture 16
The Nuclear Fuel Cycle

Spiritual Thought

2 Nephi 5:27

27. And it came to pass that we lived after the manner of happiness.

Roadmap


Nuclear Engineering
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Baryonic Matter
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Nuclear Behaviors
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6 factor formula
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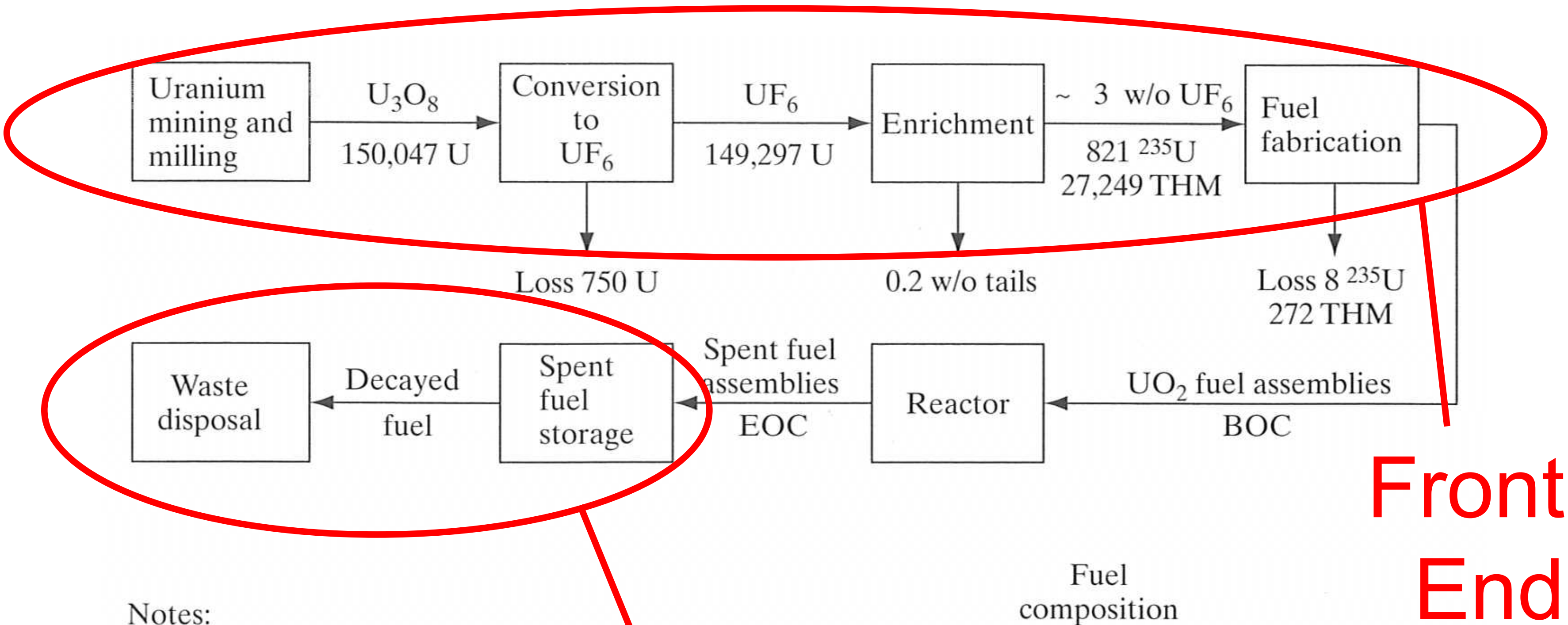
Fission and other Power Plants
Fuel Cycle

Open Fuel Cycle (LWR)



Notes:
1. Mass flows in kg's per 0.75 GWe-yr.
2. Abbreviations:
   - BOC = beginning of refueling cycle
   - EOC = end of refueling cycle
   - FP = fission products
   - Pu = total plutonium
   - Pu fissile = $^{239}Pu + ^{241}Pu$
   - THM = total heavy metal = U + Pu
   - U = total uranium

Back End

Fuel composition

	BOC	EOC
^{235}U	813	220
U	26,977	25,858
Pu fissile	—	178
Pu	—	246
THM	26,977	26,104
FP	—	873

Grades of Uranium

- Depleted uranium (DU) contains < 0.7% U-235
- Natural uranium contains 0.7% U-235
- Low-enriched uranium (LEU) contains > 0.7% but < 20% ^{235}U
- Highly enriched uranium (HEU) contains > 20% ^{235}U
- Weapons-grade uranium contains > 90% ^{235}U
- Weapons-usable uranium – lower than weapons grade but usable after ignition in a weapon

Isotope Separation Techniques

- Laser-based
  - Potentially highly efficient and effective
  - Requires sophisticated optics and components
- Electromagnetic
  - Very expensive
  - Similar to mass spectrometer
  - Possibly useful at small scale
- Thermal Diffusion
  - Based on thermal diffusion effects
  - Historically significant as U supply
- Gaseous diffusion
  - Example of membrane separation technique
- Aerodynamic
  - Relatively new and less developed than most other techniques
- Centrifugal
  - Requires high-speed, high-strength centrifuges
  - Common current method of separation
- Chemical
  - Useful for light isotopes
  - Research stages otherwise

Enrichment Balances

- Develop a Balance for Uranium Enrichment:

$$F = P + W$$

$$x_f F = x_p P + x_w W$$

- F = number of kilograms of feed material (kg/s)
- P = number of kilograms of product enriched (kg/s)
- W = number of kilograms of uranium in the waste stream (kg/s)
- x_f = weight fraction of ^{235}U in the feed
- x_p = weight fraction of ^{235}U in the product (i.e. desired enrichment)
- x_w = weight fraction of the ^{235}U in the waste stream (i.e. depleted U)

Relationships

- Feed Factor, or F/P?

$$\frac{F}{P} = \frac{x_p - x_w}{x_f - x_w}$$

- Waste Factor, or W/P?

$$\frac{W}{P} = \frac{x_p - x_f}{x_f - x_w}$$

Separative Work Units (SWU)

- A measure of the work required to "separate" ^{235}U, or enrich natural U:

$$SWU = \left[P \cdot V\left(x_p\right) + W \cdot V(x_w) - F \cdot V(x_F)\right]t$$

$$V(x_i) = (2x_i - 1)ln\left(\frac{x_i}{1 - x_i}\right)$$

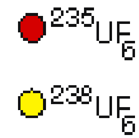
SWU/kg = $V\left(x_p\right) + \frac{W}{P} \cdot V(x_w) - \frac{F}{P} \cdot V(x_F)$

Example Problem

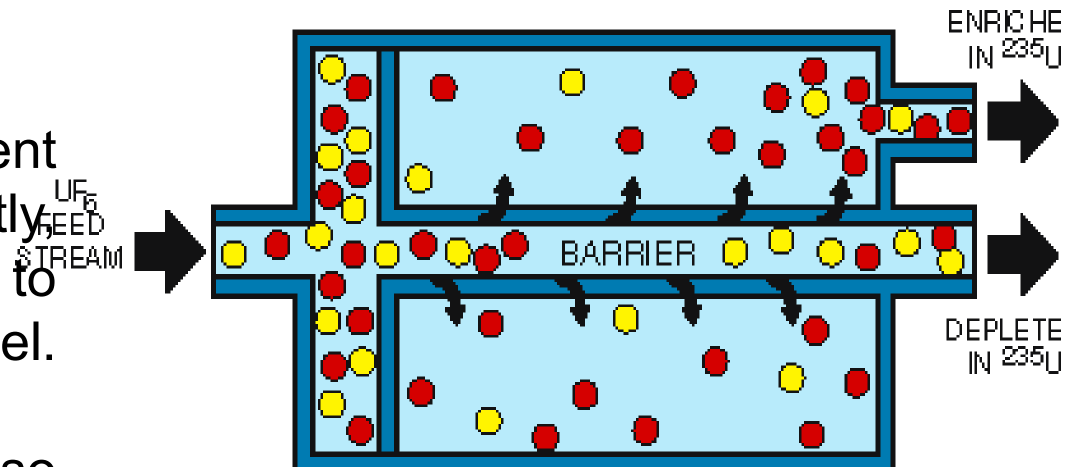
- What is the specific SWU (SWU/kg) requirement to enrich U to 5% assuming a tails enrichment of 0.1%? Assuming a tails enrichment of 0.01%?

Gaseous Diffusion

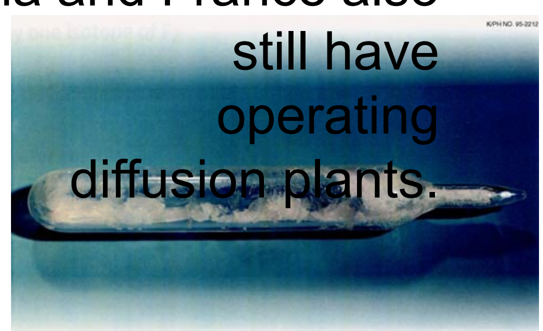
Relies on molecular effusion (the flow of gas through small holes) to separate U-235 from U-238. The lighter gas travels faster than the heavier gas. The difference in velocity is small (about 0.4%). So, it takes many cascade stages to achieve even LEU.



U.S. first employed this enrichment technique during W.W. II. Currently, only one U.S. plant is operating to produce LEU for reactor fuel.



China and France also still have operating diffusion plants.



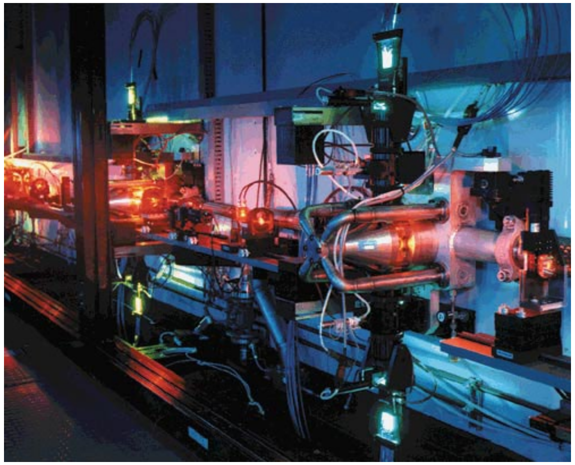
Uranium hexafluoride UF_6: Solid at room temperature.

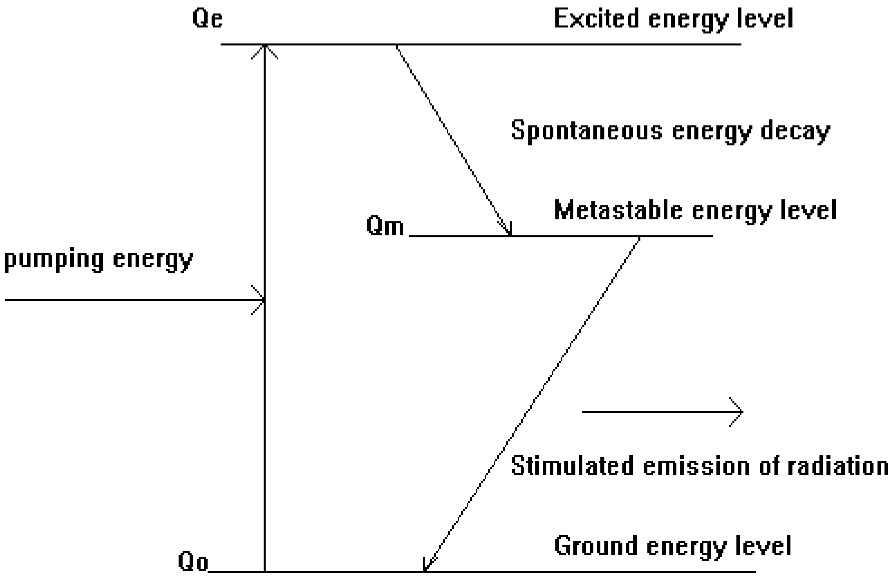
Gaseous Diffusion: What's Needed for 25 kilograms of HEU per Year?

- At least one acre of land
- 3.5 MW of electrical power
- Minimum of 3,500 stages, including:
  - Pumps, cooling units, control valves, flow meters, monitors, and vacuum pumps
- 10,000 square meters of diffusion barrier with sub-micron-sized holes

Laser Isotope Separation

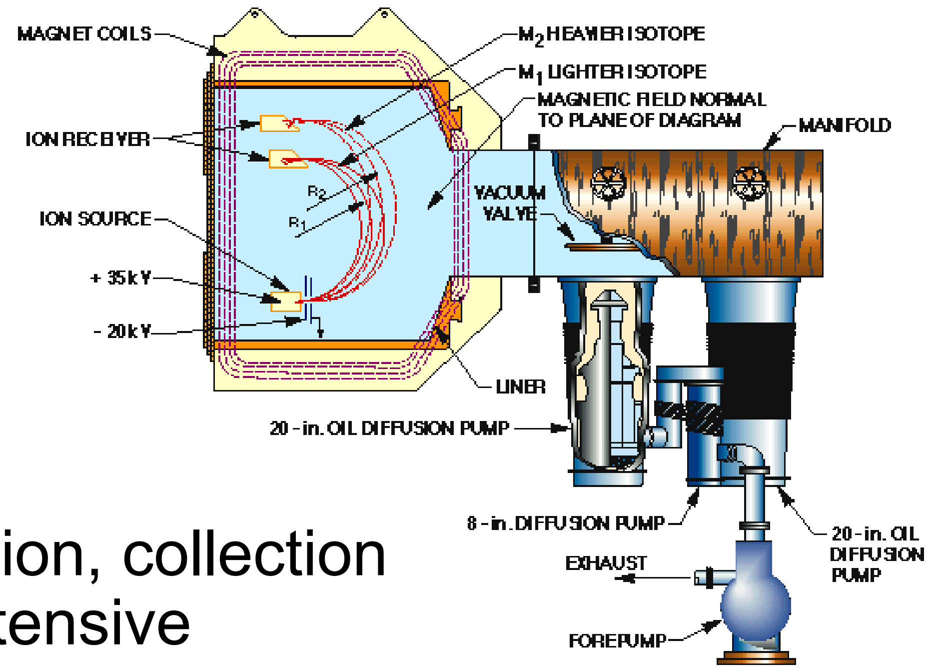
- Uses lasers to separate ^{235}U from ^{238}U
- Lasers selectively excite one isotope (502.74 nm vs. 502.73 nm for ^{238}U and ^{235}U, respectively)
- Highly specialized technology and equipment





Electromagnetic Isotope Separation

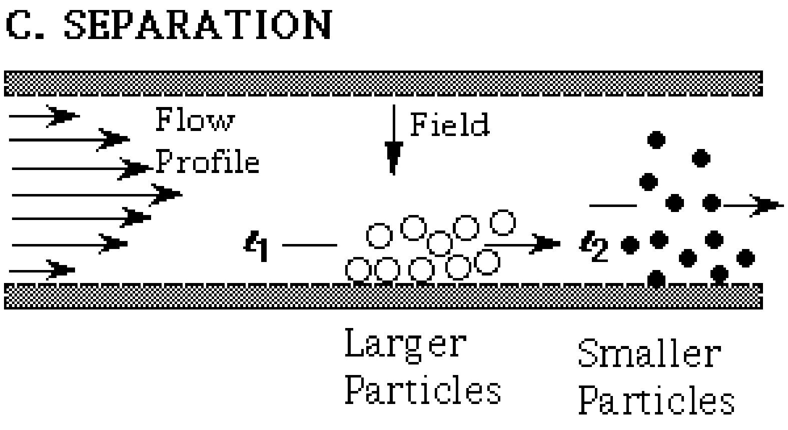
- Uranium tetrachloride (UCl_4) is vaporized and ionized.
- An electric field accelerates the ions to high speeds.
- Magnetic field exerts force on UCl_4^+ ions
- Less massive U-235 travels along inside path and is collected



- Disadvantages:
  - Inefficient: 50% ion production, collection
  - Time consuming/Energy Intensive
  - UCl_4 is very corrosive.
  - Large Staffing Requirements
- Advantage:
- Could be hidden in a shipyard or factory – could be hard to detect
  - ➢Although all five recognized nuclear-weapon states had tested or used EMIS to some extent, this method was thought to have been abandoned for more efficient methods until it was revealed in 1991 that Iraq had pursued it.

Thermal Diffusion

- Uses difference in heating to separate light particles from heavier ones.
- Light particles preferentially move toward hotter surface.
- Not energy efficient compared to other methods.
- Used for limited time at Oak Ridge during WW II to produce approximately 1% U-235 feed for EMIS. Plant was dismantled when gaseous diffusion plant began operating.

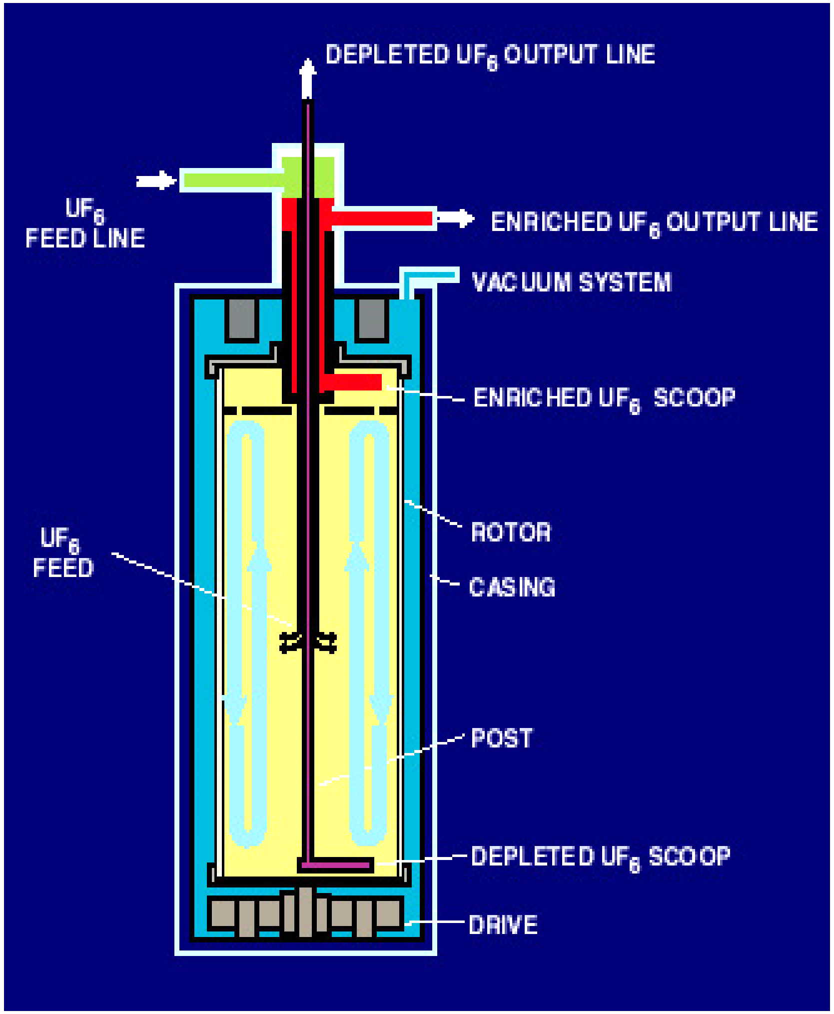


Aerodynamic Processes

- Developed and used by South Africa with German help for producing both LEU for reactor fuel and HEU for weapons.
- Mixture of gases (UF_6 and carrier gas: hydrogen or helium) is compressed and directed along a curved wall at high velocity.
- Heavier U-238 moves closer to the wall.
- Knife edge at the end of the nozzle separates the U-235 from the U-238 gas mixture.
- Proliferant state would probably need help from Germany, South Africa, or Brazil to master this technology.

Gas Centrifuge

- Uses physical principle of centripetal force to separate U-235 from U-238
- Very high speed rotor generates centripetal force
- Heavier $^{238}UF_6$ concentrates closer to the rotor wall, while lighter $^{235}UF_6$ concentrates toward rotor axis
- Separation increases with rotor speed and length.



Back End of Fuel Cycle

- Buildup of Isotopes
  1. Transuranics (long lived)
  2. Fission products
     - Gaseous
     - Solid
  3. Leftover Fuel
- 3 Major Challenges
  – Radioactivity & Heat Loading are high
  – Difficult to separate problem isotopes
  – VERY Long lived ~800k years to natural levels

Spent fuel in US

Transuranic Waste (TRUW)

- Transuranic Waste (TRUW)
  - Alpha-emitting actinides
  - Half lives > 20 years
  - Activity > 100 nCi/g.
  - Mostly from weapons manufacture mostly (Pu)
  - Rags, clothing, and other shop materials.
  - Stored at the Waste Isolation Pilot Plant in NM.
- Generally less potent than spent fuel

Typical LWR Fuel Compositions

Fuel

Atom %	New	Spent
^{238}U	96.7	94.3
^{235}U	3.3	0.81
^{236}U		0.51
^{239}U		0.52
^{240}U		0.21
^{241}U		0.10
^{242}U		0.05
Fiss. prod.*		3.5

Solid Fission Products

	$T_{1/2}$	Spent
^{90}Sr	29.1 y	94.3
^{137}Cs	30.2 y	0.81
^{99}Te	0.21 My	0.51
^{79}Se	1.1 My	0.52
^{93}Zr	1.5 My	0.21
^{135}Cs	2.3 My	0.10
^{129}I	16 My	0.05

main long-term actors

essentially stable

Seven fission products w/ $T_{1/2}$ > 25 years
Activity less than ore after 1 ky

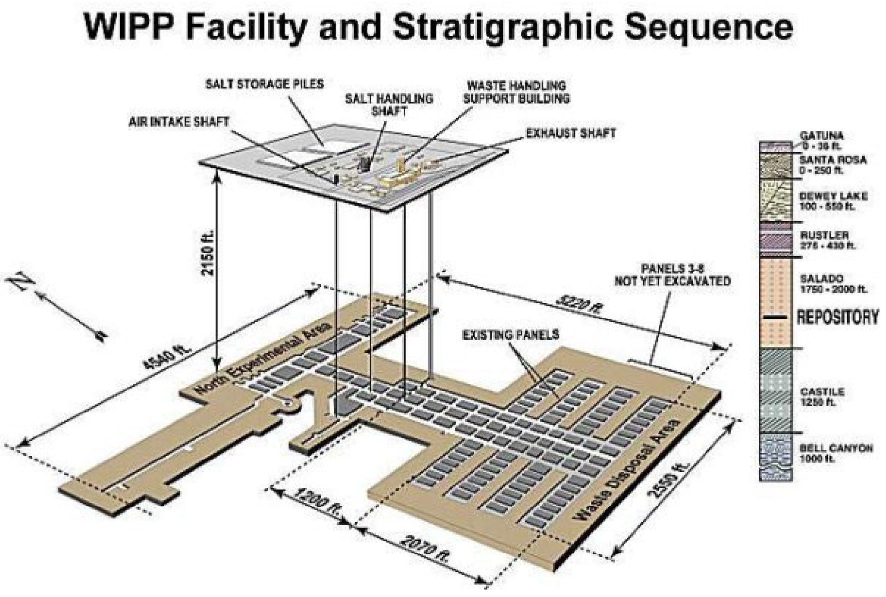
^{239}Pu $T_{1/2}$ = 24 ky – major waste issue

Radiopharmaceuticals

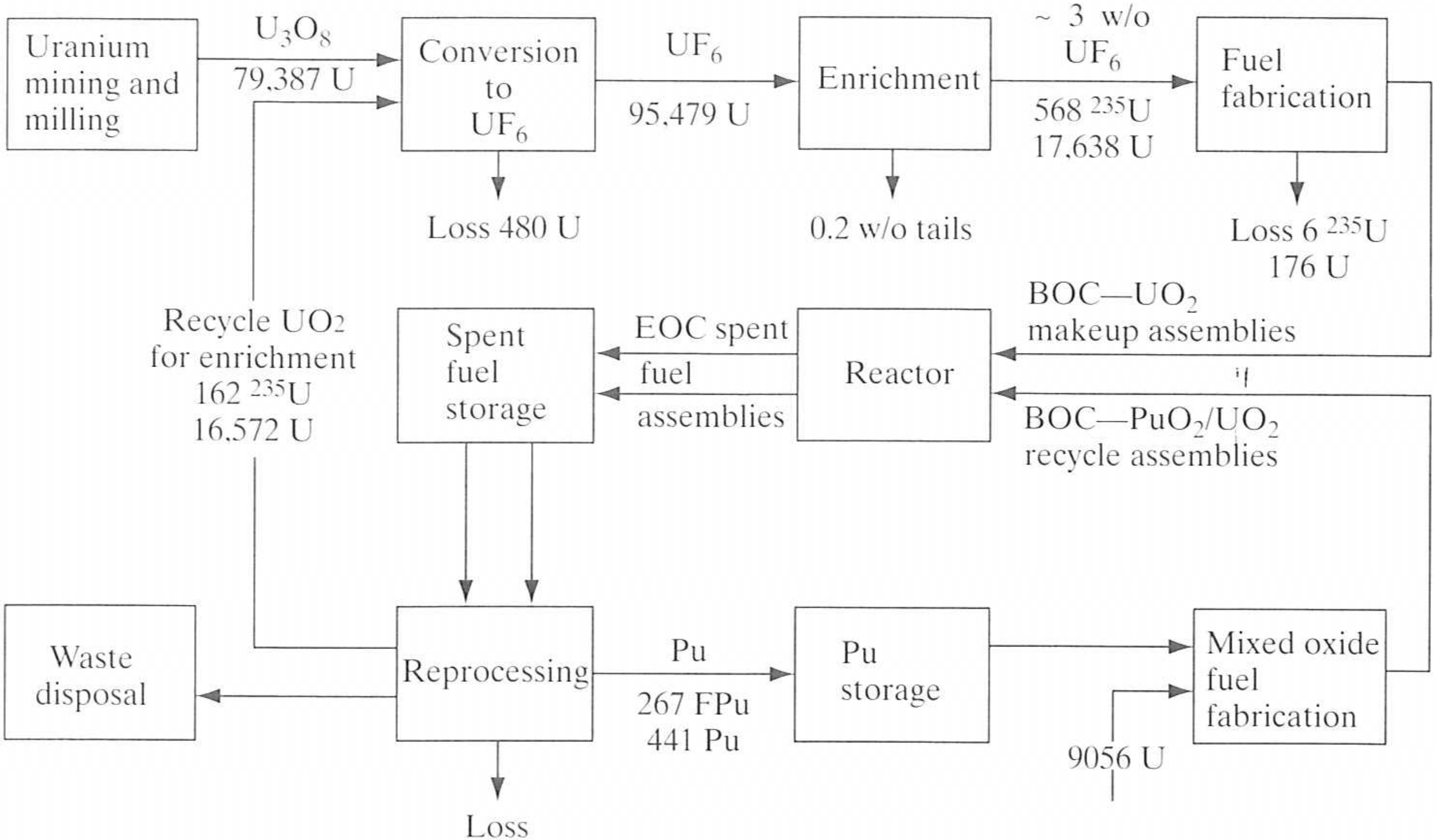
- Calcium-47
- Carbon-11
- Carbon-14
- Chromium-51
- Cobalt-57
- Cobalt-58
- Erbium-169
- Fluorine-18
- Gallium-67
- Hydrogen-3
- Indium-111
- Iodine-123
- Iodine-131
- Iron-59
- Krypton-81m
- Nitrogen-13
- Oxygen-15
- Phosphorus-32
- Samarium-153
- Selenium-75
- Sodium-22
- Sodium-24
- Strontium-89
- Technetium-99m
- Thallium-201
- Xenon-133
- Yttrium-90

WIPP

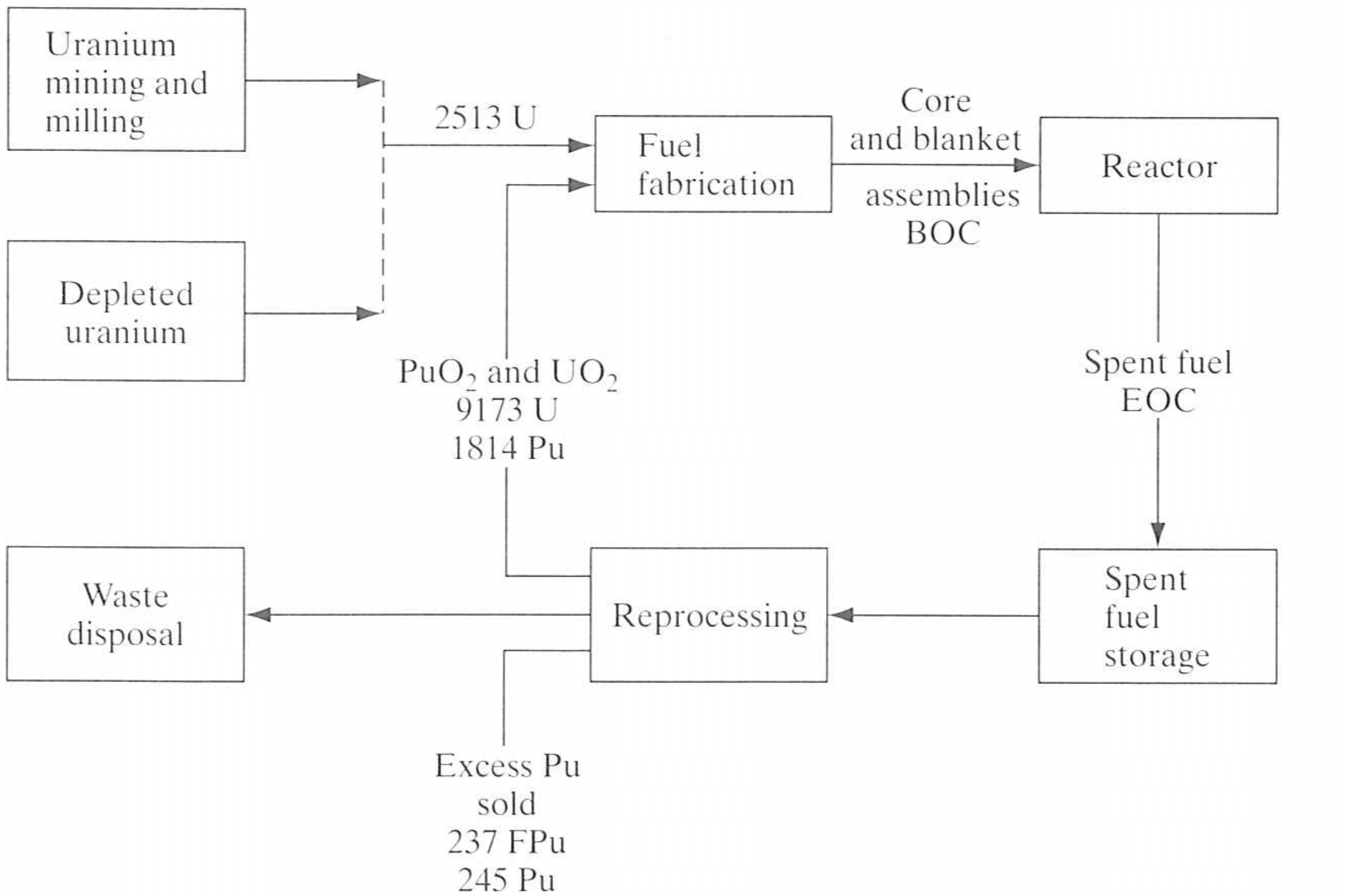
- One of 3 operating sites for long-term storage, located in a NM salt dome.
- Transuranic radioactive waste for 10,000 years that is left from the research and production of nuclear weapons.
- 1973 initial site
- 1979 construction authorized
- 1990s – testing 28 organizations thought they were in charge (congress and EEG state agency main roles)
- 1999 – first shipment
- Far future – communication and warning messages for next 10,000 years



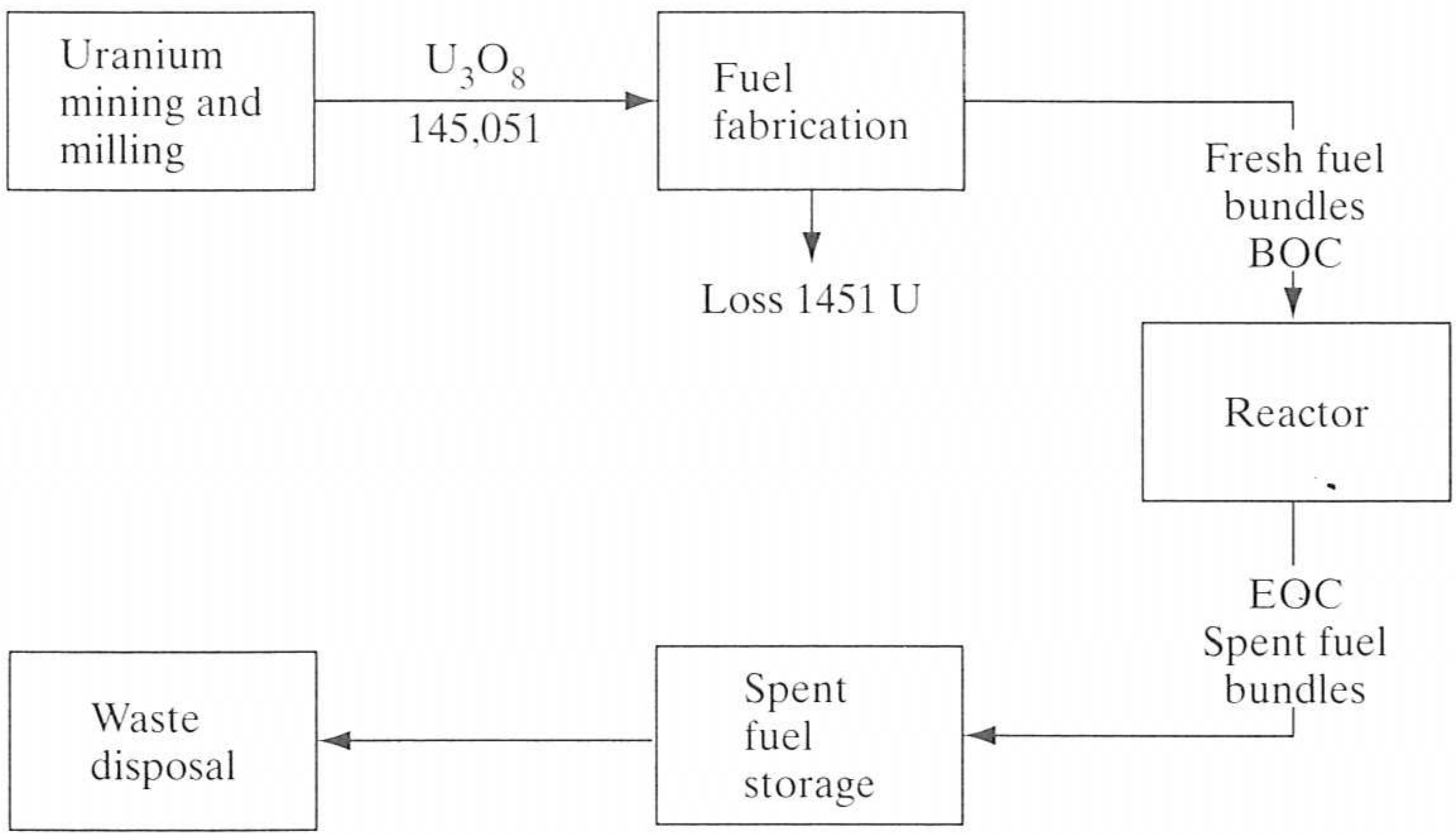
Pu and U recycle (LWR)



Breeder Fuel Cycle (LMFBR)



Open CANDU Fuel Cycle



Fuel Cycle Impacts on Resources

Plant (Reactor) Types and Cycle	Natural Uranium Requirements (*t*)
LWR	
Once-through	4,260
U-Pu recycling	2,665
HWR	
Natural uranium, once-through	3,655
Natural uranium, Pu recycling	1,820
Low-enriched uranium	2,505
LMFBR	
U-Pu recycling	36[+]

Lifetime (30 yr) fuel requirements, 1 GW_e, 70% available