# Chemical Engineering 412

*Introductory Nuclear Engineering*

Lecture 16

The Nuclear Fuel Cycle

Review

# Spiritual Thought

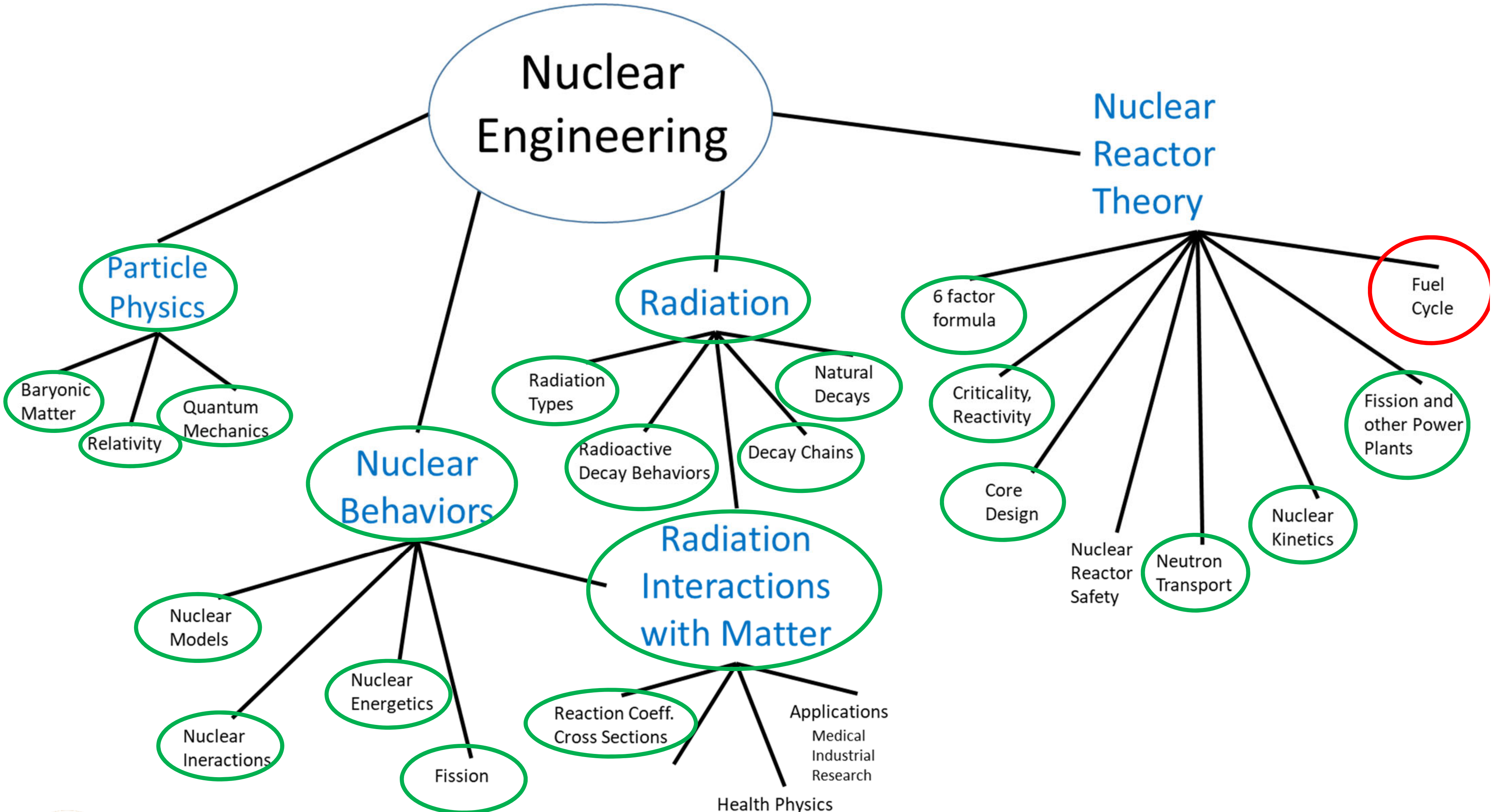
I realize that there are some, perhaps many, [who] feel overwhelmed by the lack of time. You have left unfinished tasks in your Church calling. You've carried your scriptures all day but still have not found a moment to open them. There is someone in your family who would be blessed by your thoughtful attention, but you haven't gotten to them yet…Rather than finding ways to capture leisure time for learning, you are trying to decide what to leave undone.

There is another way to look at your problem of crowded time. You can see it as an opportunity to test your faith. The Lord loves you and watches over you. He is all-powerful, and He promised you this: "But seek ye first the kingdom of God, and his righteousness; and all these things shall be added unto you"

That is a true promise. When we put God's purposes first, He will give us miracles. If we pray to know what He would have us do next, He will multiply the effects of what we do in such a way that time seems to be expanded. He may do it in different ways for each individual, but I know from long experience that He is faithful to His word.

President Henry B. Eyring

# Roadmap


Nuclear Engineering
Particle Physics
Baryonic Matter
Relativity
Quantum Mechanics
Nuclear Behaviors
Nuclear Models
Nuclear Ineractions
Nuclear Energetics
Fission
Radiation
Radiation Types
Natural Decays
Radioactive Decay Behaviors
Decay Chains
Radiation Interactions with Matter
Reaction Coeff. Cross Sections
Applications
Medical
Industrial
Research
Health Physics
Nuclear Reactor Theory
6 factor formula
Criticality, Reactivity
Core Design
Nuclear Reactor Safety
Neutron Transport
Nuclear Kinetics
Fission and other Power Plants
Fuel Cycle

# 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:

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

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

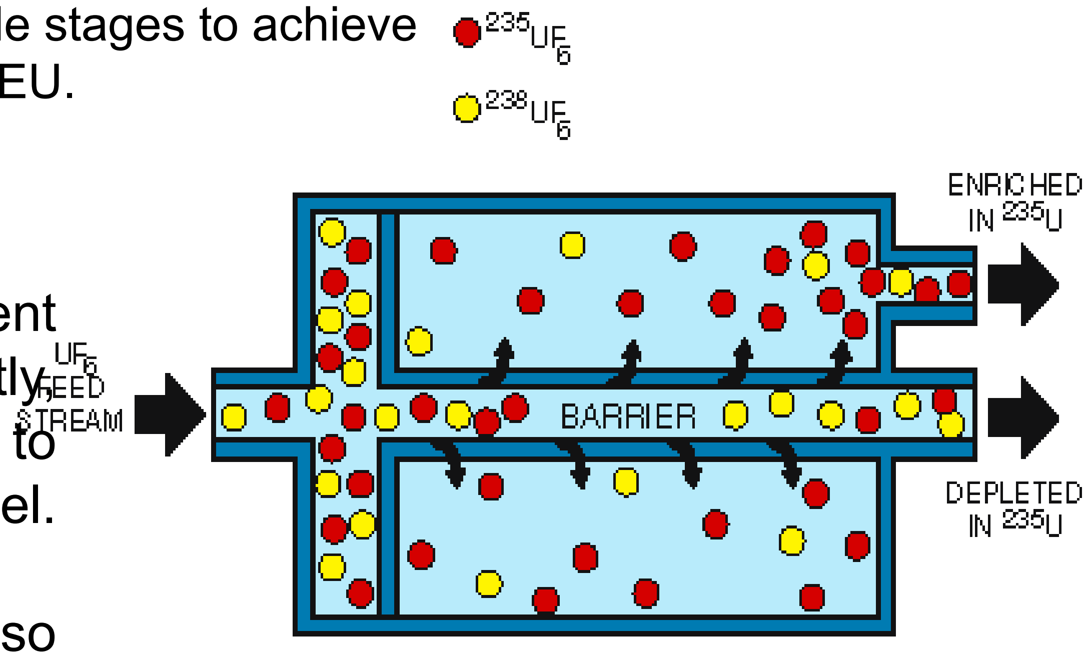
SWU/kg = $V\left(x_p\right) + \frac{W}{P} \cdot V(x_w) - \frac{F}{P} \cdot V(x_F)$

# 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%?

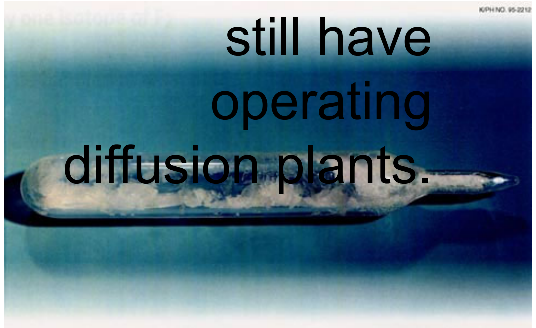
# Gaseous Diffusion

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.



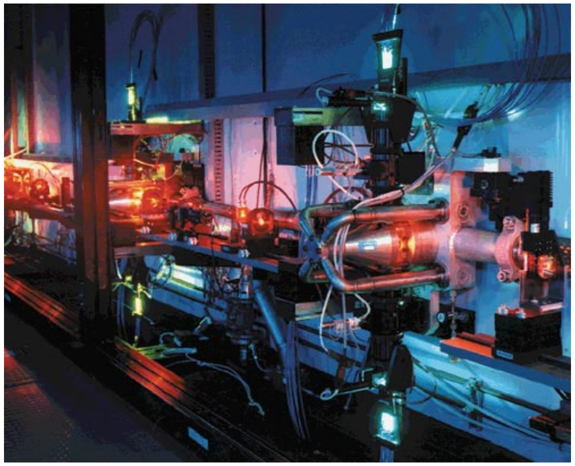
Uranium hexafluoride $UF_6$: Solid at room temperature.

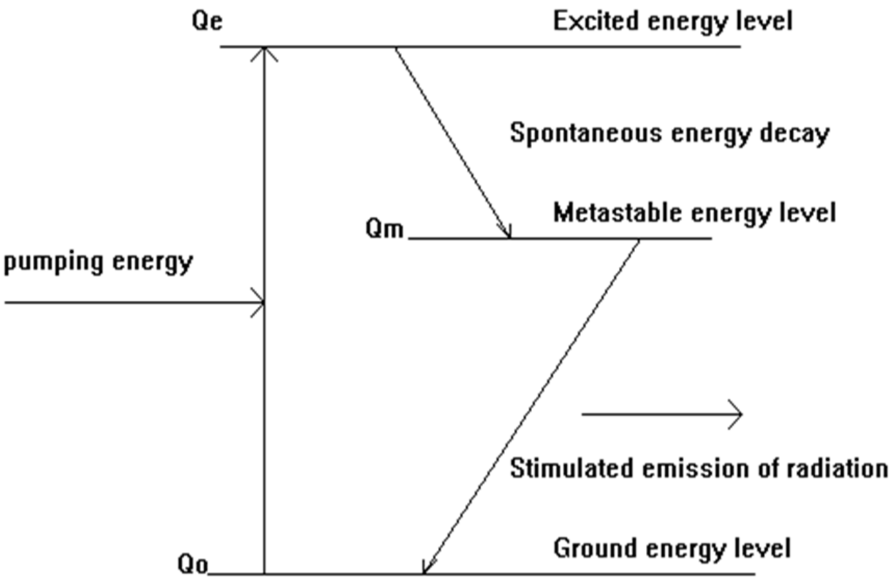
# Gaseous Diffusion: What's Needed for 25 kilograms of HEU per Year?

- 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

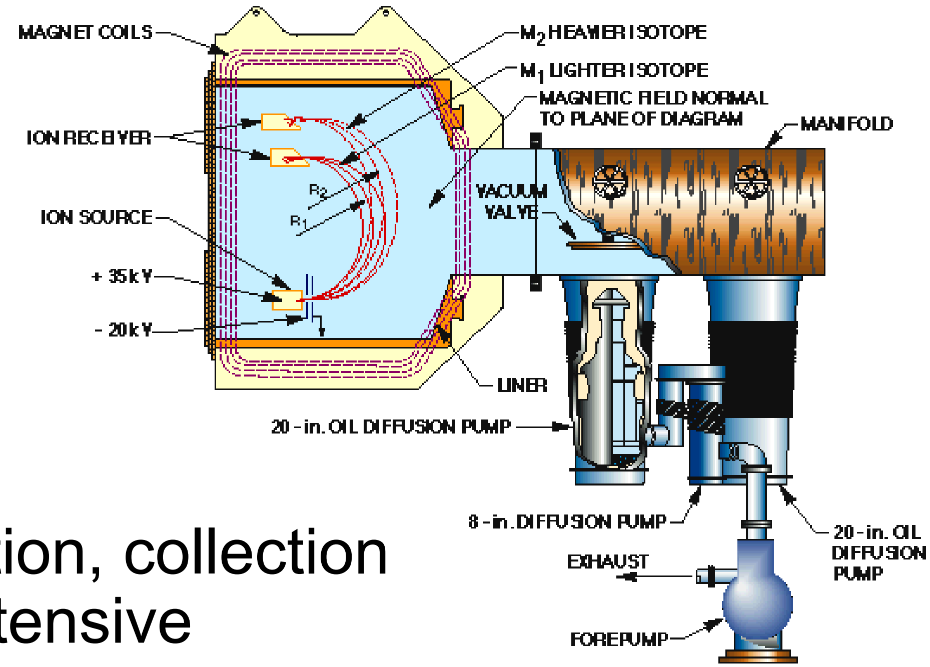
- Uses lasers to separate $^{235}U$ from $^{238}U$
- Lasers selectively excite one isotope (502.74 nm vs. 502.73 nm for $^{238}U$ and $^{235}U$, respectively)
- Highly specialized technology and equipment





# Electromagnetic Isotope Separation

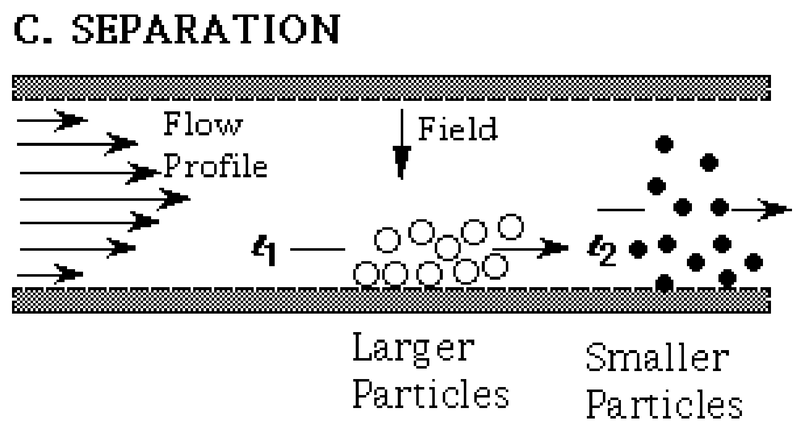
- Uranium tetrachloride ($UCl_4$) is vaporized and ionized.
- An electric field accelerates the ions to high speeds.
- Magnetic field exerts force on $UCl_4^+$ ions
- Less massive U-235 travels along inside path and is collected




- 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.

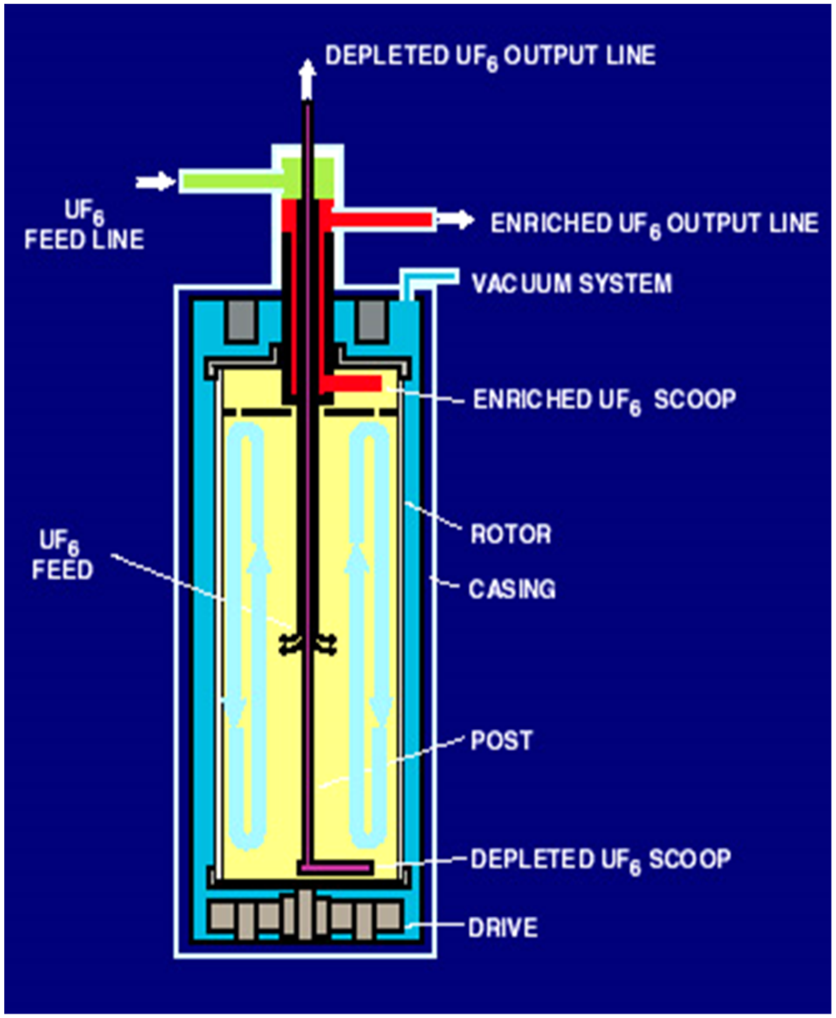


# Aerodynamic Processes

- 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
  - Transuranics (long lived)
  - Fission products
    - Gaseous
    - Solid
- 3 Major Challenges
  - Radioactivity & Heat Loading are high
  - Difficult to separate problem isotopes
  - VERY Long lived ~800k years to natural levels

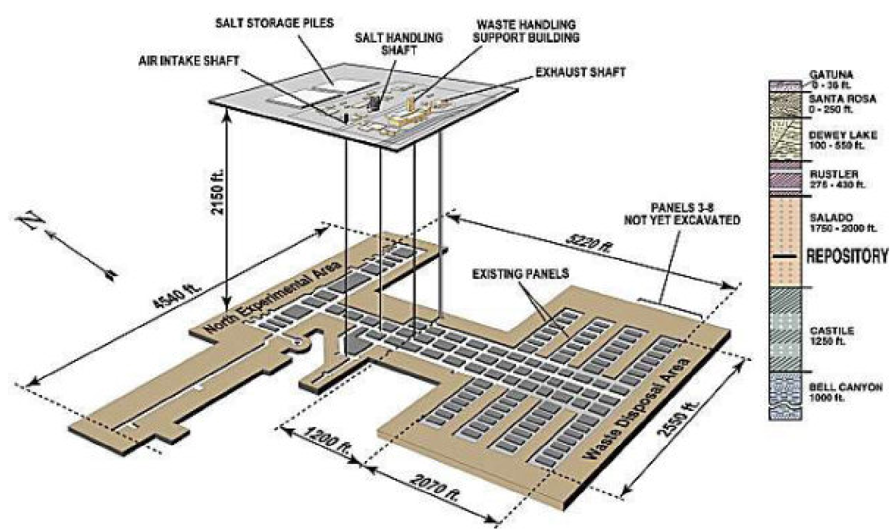
# Radiopharmaceuticals

- 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

**WIPP Facility and Stratigraphic Sequence**



# Chapter 10 (I)

- Chapter 10
  - Criticality
    - Six factor formula
    - Multiplication factor
    - Cross Sections
    - Neutron Life Cycle
  - Moderation
    - Common moderators
    - Most effective moderators
  - Bare Reactor
    - Flux profiles
    - Boundary conditions
    - Diffusion Equation Problems

# Chapter 10 (II)

- Homogenous vs. heterogeneous
- Buckling
  - Geometric
  - Material
  - Constituents
  - How to size reactor
- Transient Reactor Behavior
  - Delayed neutrons
  - reactivity
  - $\delta k$
  - Reactor worth ($)
  - Reactor operation
  - Period and times

# Chapter 10 (III)

- Poisons
  - Reactivity insertions
  - Reactivity “swing”
  - Reactor control methods
  - Long term reactivity changes and countermeasures
  - Changes in time
- Reactivity Coefficients
  - Doppler
  - Void (moderator expansion)
  - Axial Expansion
  - Radial Expansion
  - Control Rod Drive Expansion
  - Calculate change in reactivity based on given coefficients

# Chapter 11 (I)

- Nuclear Energy Conversion
  - Key Components
  - General layout of nuclear plant systems
- Light Water Reactors
  - Components
  - Configurations
  - Design
  - Challenges
  - Operation
  - BWR vs PWR
- Operation Perturbations
  - Thermal Changes
  - Load Changes
  - Fuel Changes
  - Accidents

# Chapter 11 (II)

- Gen IV Reactors
  - Know types
  - Benefits/Disadvantages
- Evolution of Nuclear Power
  - Generations
  - Characteristics
  - Other Non-LWR (non Gen IV)
- Fast Reactors
  - Breeder vs. Burner
  - Key Components
  - Challenges
  - World-wide use

# Chapter 12

- heat output of radioactive isotopes.
- GPHS
  - Characteristics
  - Table 12.2
- RTGs
  - Types
  - Differences & Similarities
- Electricity generation at any point in the life of an RTG.
- Space reactor concepts

# Example 1: Back to the Future

- Equate Bucklings
  - Geometric – Easy
  - Material – significantly harder (why?)
- Simplest approach
  - Assume homogenous core
  - Assume single energy
  - Assume number density ratio based on movie
  - Find $B^2$ using the 6 factor formula ($k_{eff}$=1)

# Example 2: Rod Ejection Accident

- A control rod is ejected from the core instantly adding \$0.0005 reactivity to the core. Assuming we want a temperature increase of no more than 10 ºC, what is the minimum overall reactivity feedback coefficient (in %mil/ºC)?

$$\$.0005 = x \cdot 10^\circ C = \frac{\$.0005}{10^\circ C} = \frac{\$.00005}{^\circ C}\left|\frac{10000\ pcm}{1\$}\right. = \frac{5\ \%mil}{^\circ C}$$

- If water contributes 1 %mil/ºC of negative feedback, how much should the soluble Boron provide?

$$5\% = \Delta\rho_{water} + \Delta\rho_{Boron}$$

$$\boxed{\Delta\rho_{Boron} = 5 - 1 = 4\ \%mil/^\circ C}$$

# Chapter 11.6-11.7

- Nuclear Fuel Cycle: front and back end
- Enrichment Calculations
  - Waste factor, feed factor, separation potentials
  - Use these factors to determine cost given price
- Grades and forms of Uranium
- Separation Techniques
- LWR Fuel compositions
- Radiopharmaceuticals
- Once-through cycle
- Other fuel cycles – recycle, mixed oxides, etc.