# Chemical Engineering 412

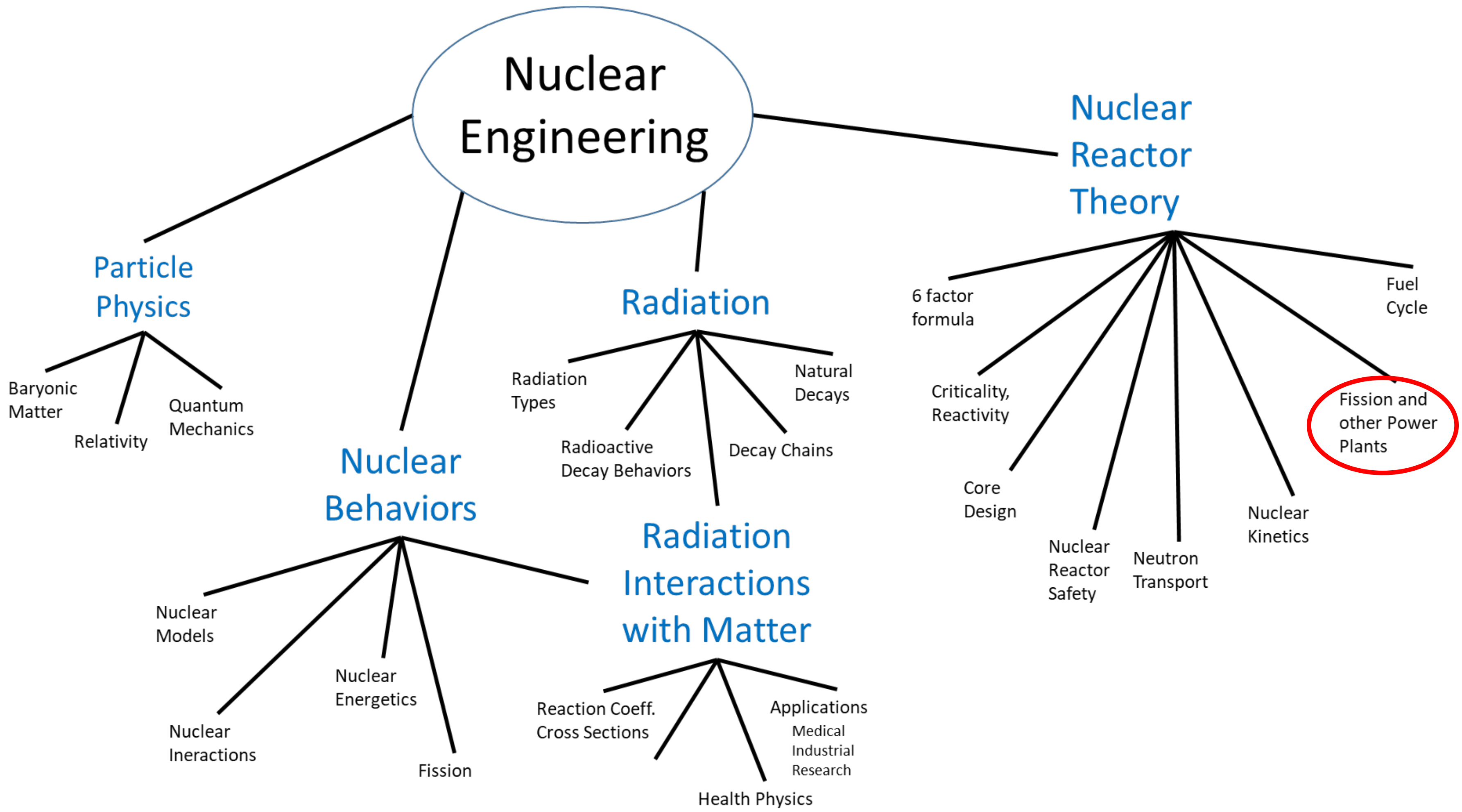
## *Introductory Nuclear Engineering*

Lecture 21

Nuclear Power Plants III

Nuclear Power Plants: Advanced Reactors

# The BIG Picture



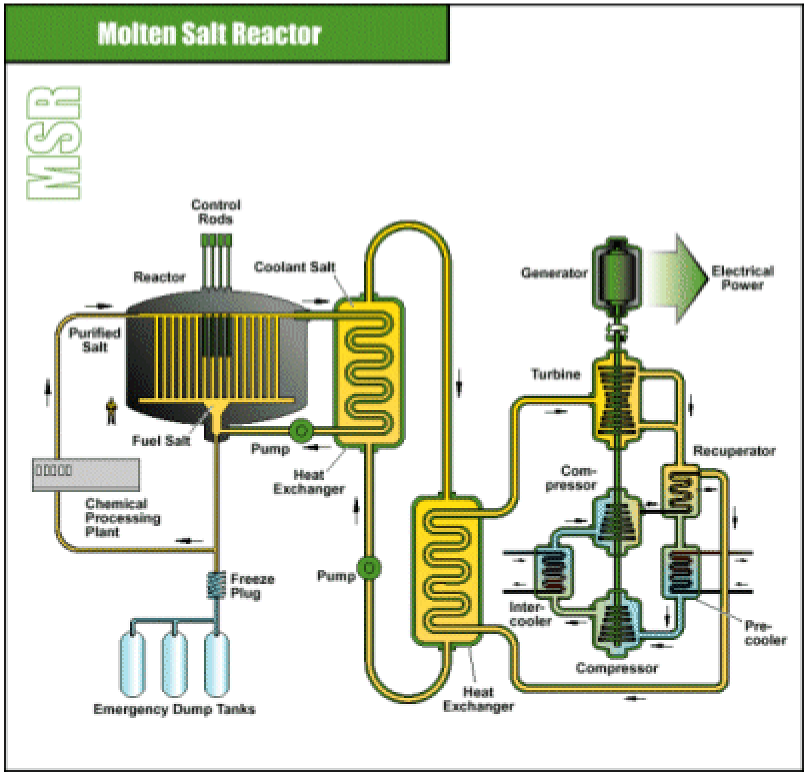
# Spiritual Thought

"It's better to look up!"

President Thomas S. Monson

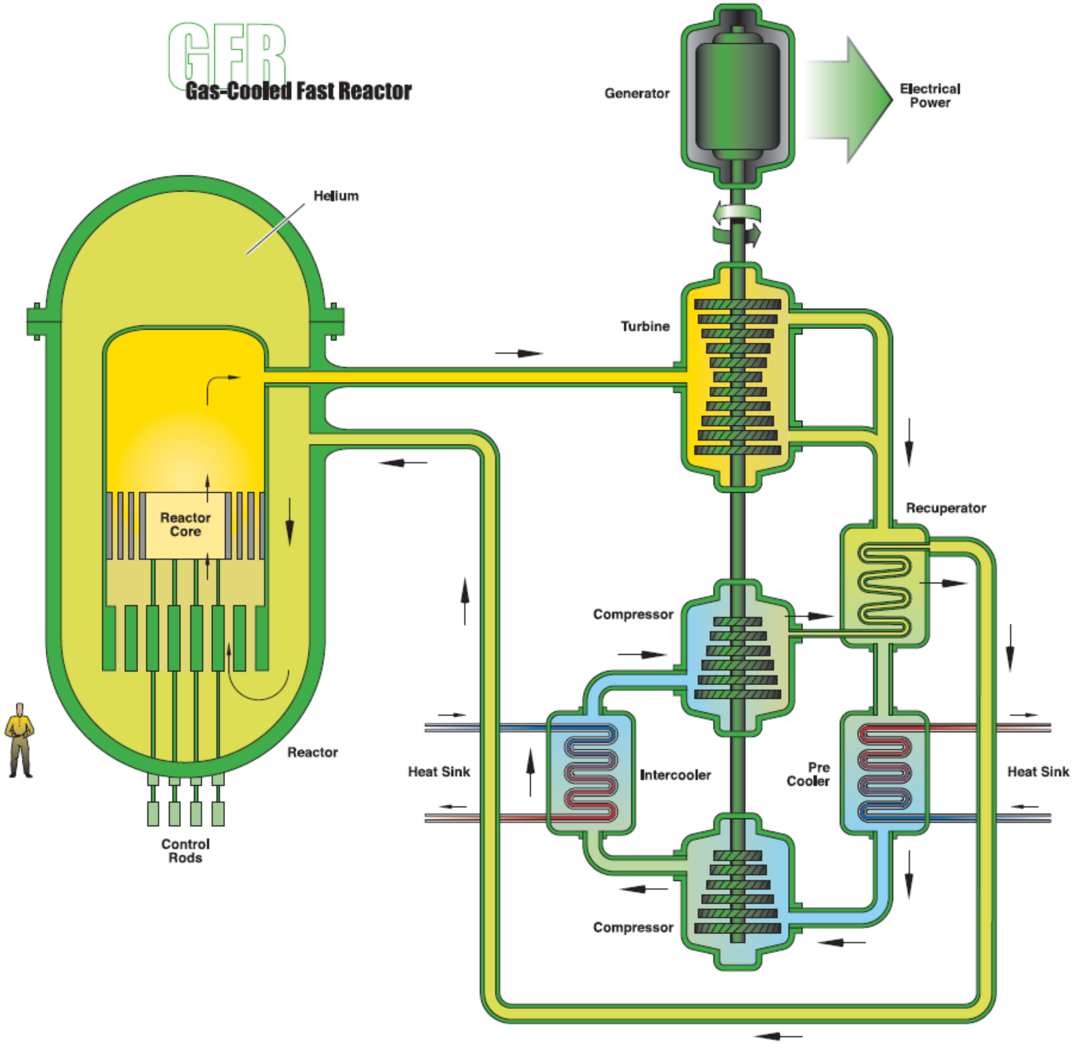
# Reactor Startup

# Molten Salt Reactor



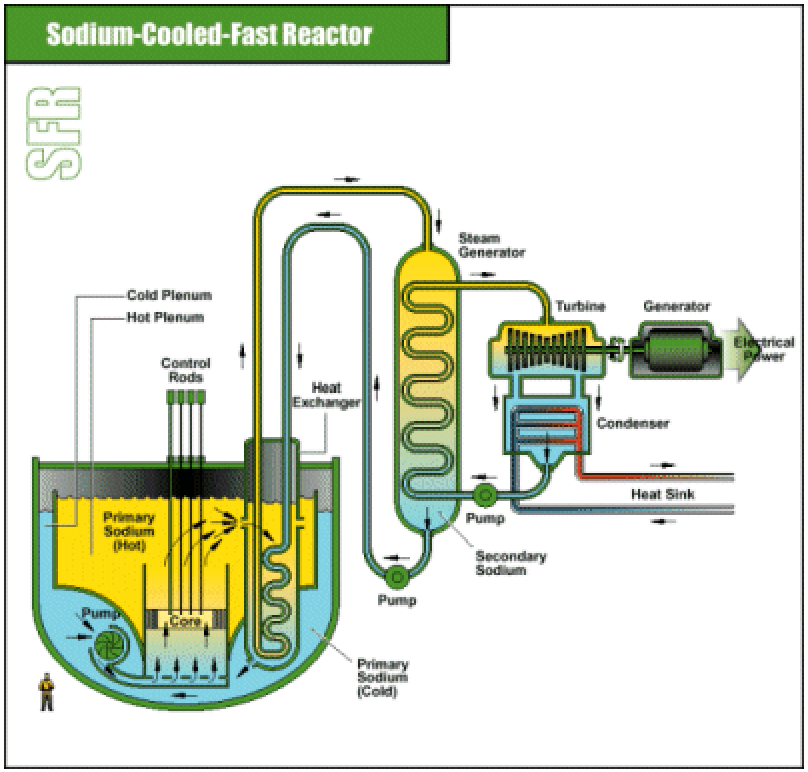

- Low-pressure, high-temperature core cooling fluid
- Fuel either dissolved in salt (typically as $UF_4$) or dispersed in graphite moderator.
- Perhaps gas-driven (He) turbine.
- Liquid Fuel, $^{235}U$ or $^{233}U$

# Gas-cooled Fast Reactor



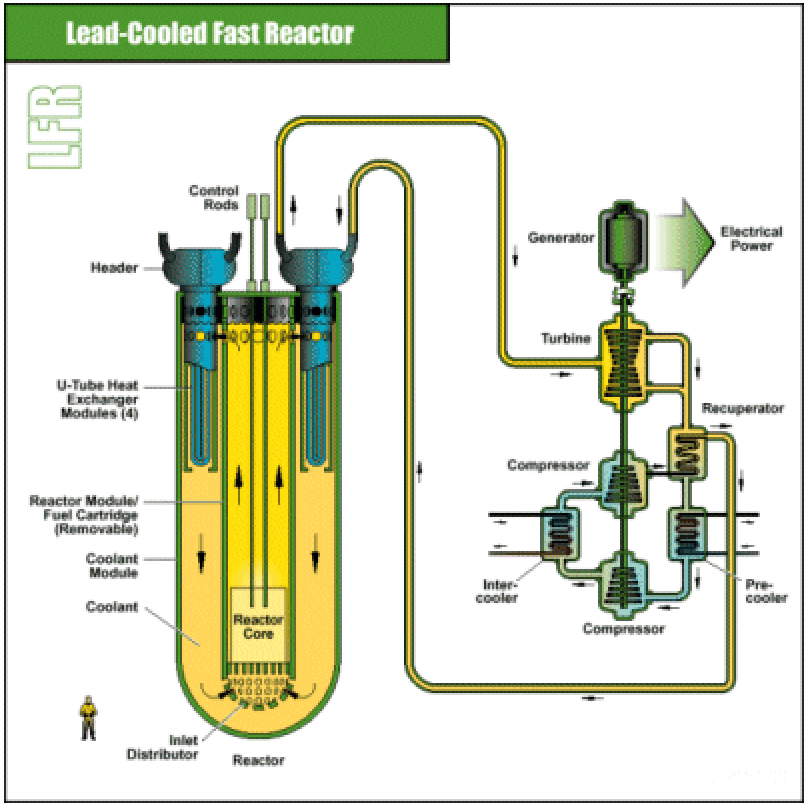

- He cooled with direct Brayton cycle for high efficiency
- Closed fuel cycle
- Low Power Density
- Fuel Rods, $^{239}Pu$

# Sodium-Cooled Fast Reactor




- Eliminates the need for transuranic (Pu) isotopes from leaving site (by breeding and consuming Pu)
- Liquid sodium cooled reactor
- Fueled by U/Pu alloy
- Fuel Rods (Zr-Pu-U metallic fuel), $^{239}$Pu

# Lead-cooled Fast Reactor




- Molten lead or lead-eutectic as core coolant
- Heat exchanged to gas-driven turbine
- Natural convection core cooling (cannot fail unless gravity fails)
- WEC Choice
- Fuel Rods (Zr-Pu-U metallic fuel), $^{239}Pu$

# Fast Reactors - Advantages

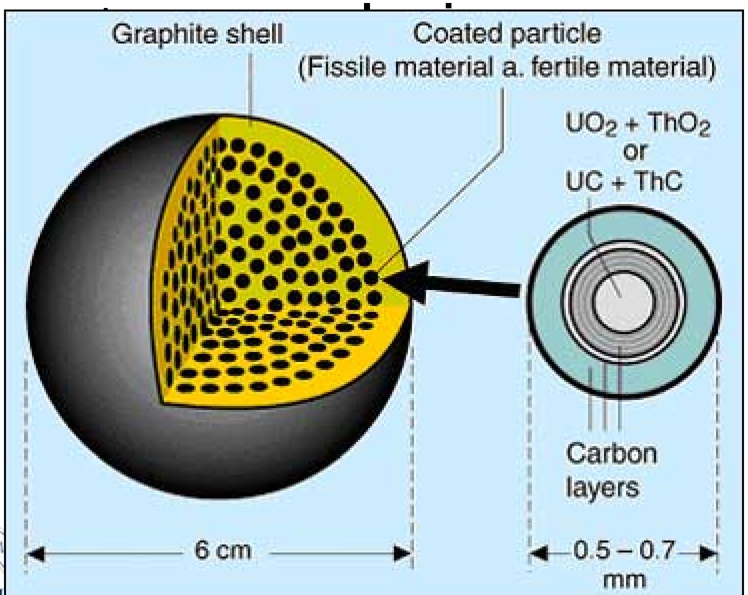
- Most transuranics act as fuel
  - Reduces waste toxicity
  - Reduces waste lifetime (dramatically)
- Expand potential fuel –
  - Thermal is primarily odd-numbered actinides ($^{235}U$)
  - Fast is all actinides, including $^{238}U$, Th, etc.
    - In waste
    - Depleted uranium
    - Actinides generated in the fuel
- When operated in breeder (as opposed to burner) mode, creates more fissionable fuel than it consumes, extending total available fuel.

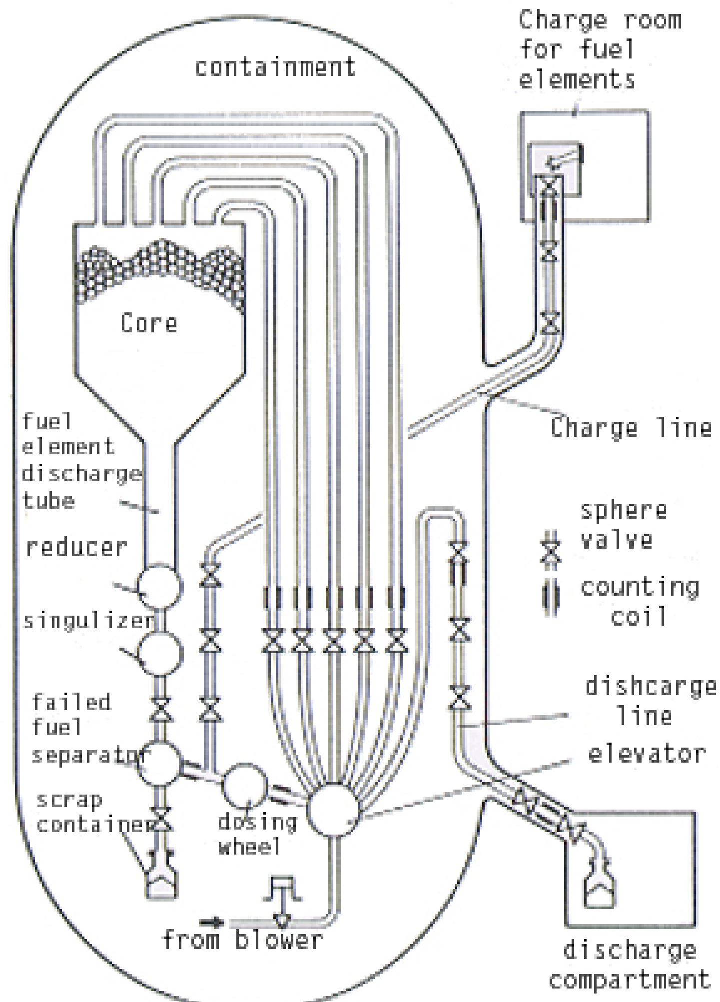
# Fast Reactors – Disadvantages

- Low response time
  - complicates control!
  - control rods less effective, other means must be used:
    - Fuel thermal expansion
    - Doppler broadening
    - Absorbers
    - Reflectors
- Small cross sections – large critical mass
  - Leads to either large cores or high enrichment.
- Sodium and sodium/potassium highly reactive!
  - Lead, salts and gases avoid this problem, but more absorption
- Liquid metals and salts can become radioactive
  - (n, $\gamma$) reactions
  - $^4$He avoids this problem (absorption cross section near zero).
- Potential positive void coefficient of liquids – not He.

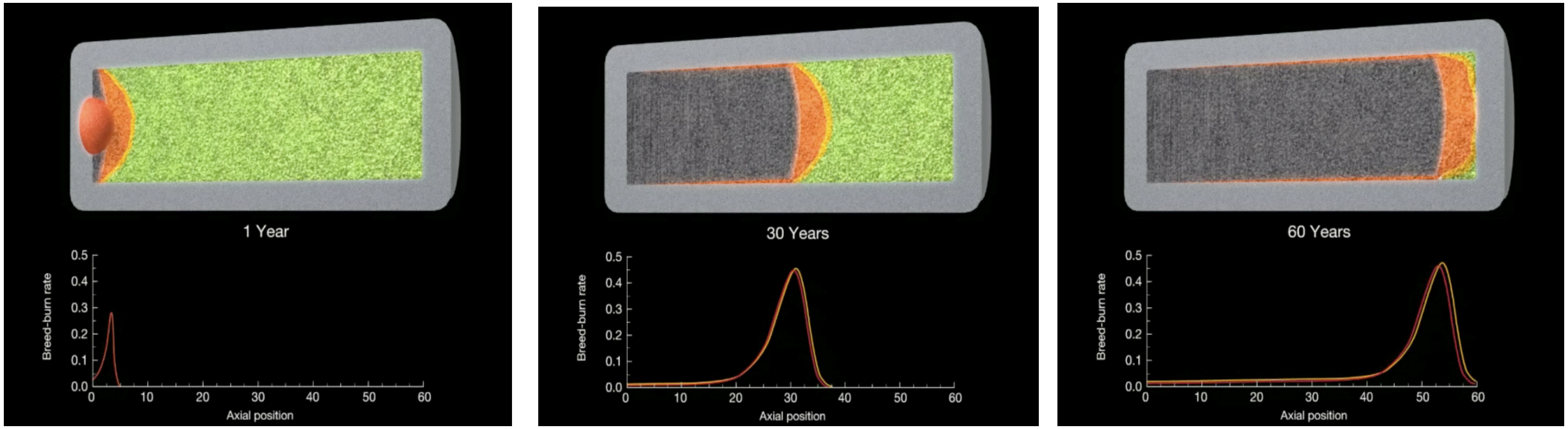
# Pebble Bed Reactor

- Inherently safe (strong Doppler effect decreases fuel reactivity with increasing temperature)
- VHTGR cannot have



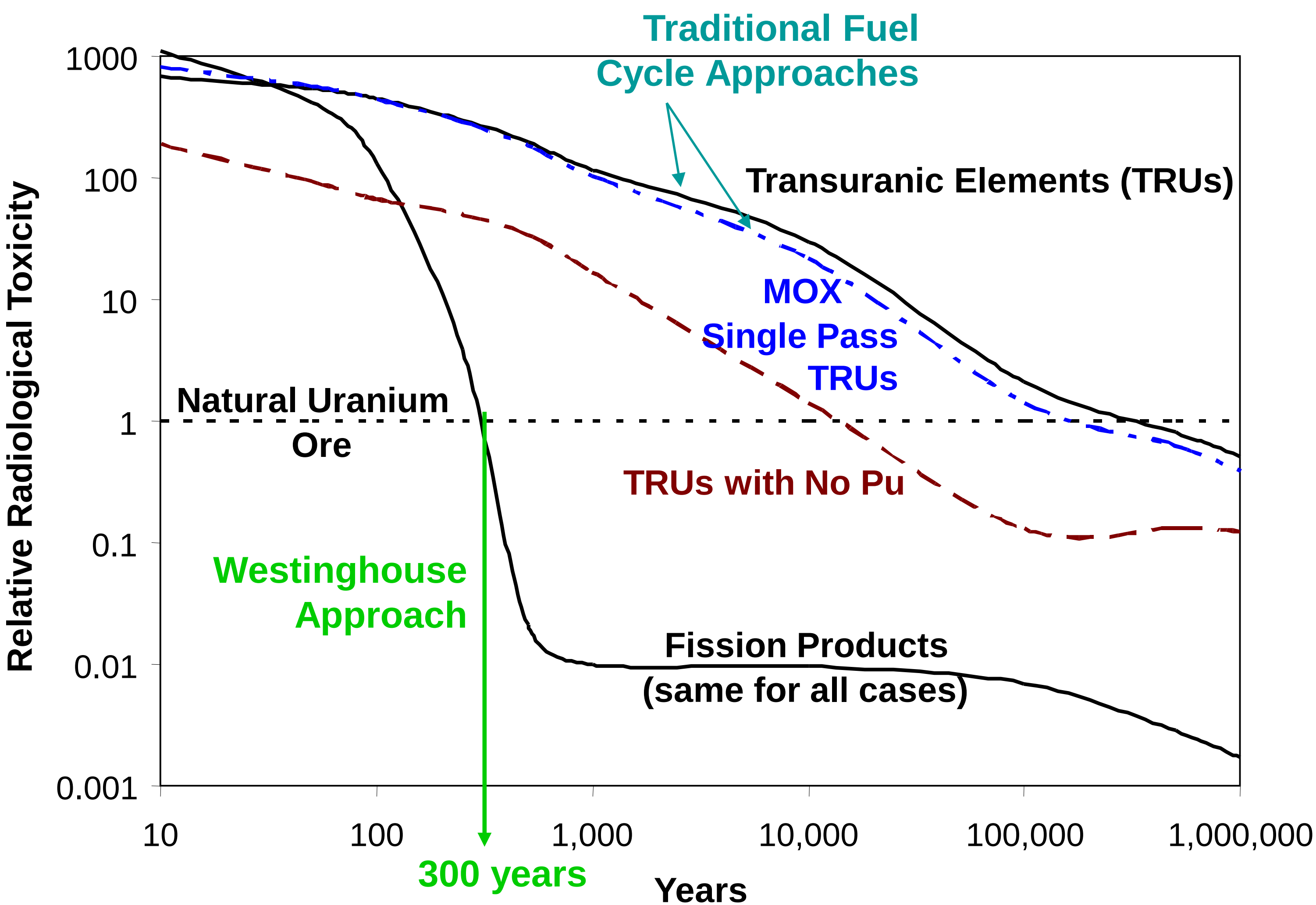



# Traveling Wave Reactor




- Fast reactor core with fission igniter buried for entire 60 year or so lifetime.
- Reaction front propagates through core in wave fashion.
- Core also is long-term containment, simplifying decommissioning and waste storage.
- Designed at both modular and utility scales

# Waste


Traditional Fuel
Cycle Approaches
1000
100
10
1
0.1
0.01
0.001
Relative Radiological Toxicity
Transuranic Elements (TRUs)
MOX
Single Pass
TRUs
Natural Uranium
Ore
TRUs with No Pu
Westinghouse
Approach
Fission Products
(same for all cases)
10
100
1,000
10,000
100,000
1,000,000
300 years
Years

# Conversion Ratio

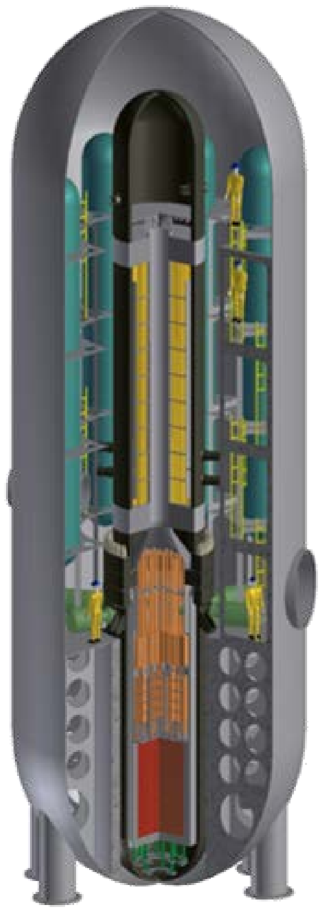
- Ratio of Created fuel to burned fuel
  - Breeder reactors 1.01 up to ~1.21
  - Burner reactors ~0.1-0.2
    - Example:
    - In a critical reactor fueled with natural uranium, it is observed that, for every neutron absorbed in 235U, 0.254 neutrons are absorbed in resonances of 238U and 0.640 neutrons are absorbed by 238U at thermal energies. There is essentially no leakage of neutrons from the reactor.
      - What is the conversion ratio?
      - How much 239Pu in kg is produced when 1 kg of 235U is consumed?

# Small Modular Reactors

- Small – < 300 $MW_e$ (IAEA definition)
  - Right size for remote grids
  - Insurance cutoff
- Modular – systems can be almost entirely fabricated in shops
  - 7, 3, 1 – factory, site, hole
  - Advantages
    - Large reduction in capital cost!
    - Reduction of financial risk
    - construction at a single location
    - ability to add incremental power.
- Disadvantages
  - Loss of economies of scale.
  - Lower Power density.
- Include III, III+, and IV or other designs

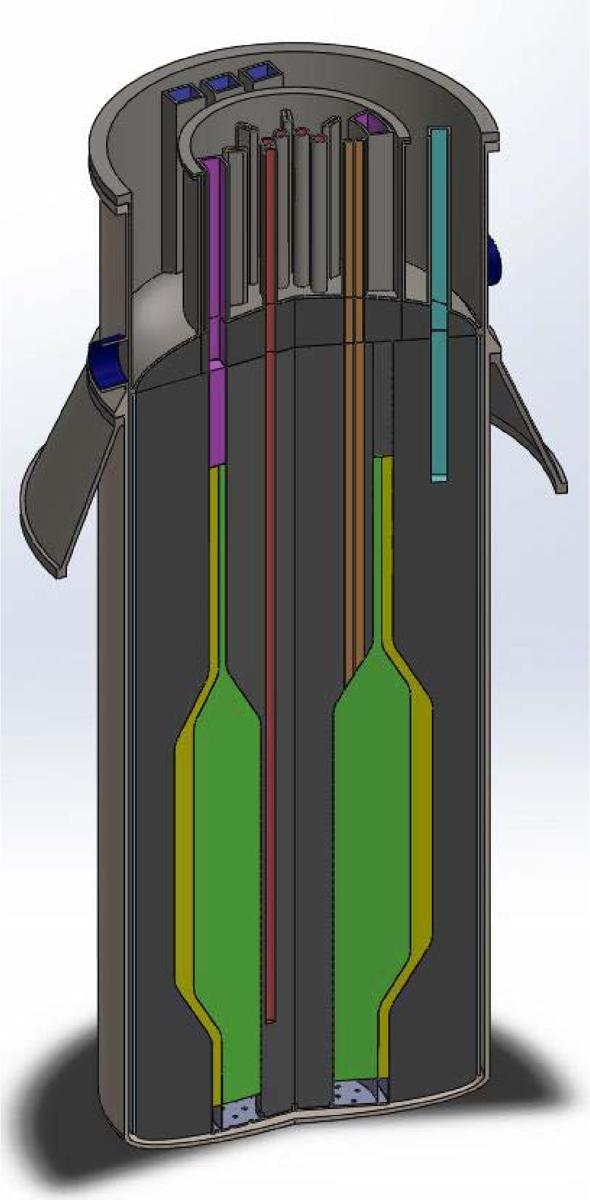
# Small Modular Reactors

- Strengths:
  - Grid Stability
    - Compact and modular
  - Economics
    - Smaller up-front investment
  - Safety
    - No-large bore piping
    - Improved passive safety (no operator action)
- Weaknesses:
  - Economics
    - Unproven, new licensing process ($1B needed)
    - Small technology improvement for $1B
  - Safety
    - Still only 7 days of passive cooling in some scenarios
  - Waste
    - No improvement on current methods



# Hybrid Designs

- Hybrid of HTGR and MSR
- Developed by both Chinese and US
  - MIT, UW, UCB + Westinghouse and INL
  - US DOE NEUP IRP 2011
- Strengths:
  - Safety
    - High thermal inertia
    - Atmospheric pressure
    - No air-ingress
    - Melt down-proof fuel
  - Grid
    - Modular, small, low investment
- Weaknesses:
  - Economics
    - Licensing, e.g. pebble locations
    - No data, high development costs
  - Safety
    - Fuel handling challenges
  - Waste
    - How to reprocess pebbles??



# Integral, Inherently Safe Light Water Reactor ($I^2S$-LWR)

- 4 Loop PWR, rated at ~1000 $MW_e$
- Designed to capture benefits of SMR concepts
  - Integral PWR; primary components in RPV
  - Elimination of large bore piping
  - Modular construction
  - Economically competitive
- Enhanced passive safety systems