Reactors and Fuels

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Short Course: Introduction to Nuclear Chemistry and Fuel Cycle Separations

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Focus On:

- Characteristics relevant to separation of used nuclear reactor fuel into its constituent parts: nuclear fuel reprocessing
  – Minimal discussion of nuclear reactors per se
- Fuels most relevant to the U.S. and separations
- Civilian nuclear power

Outline

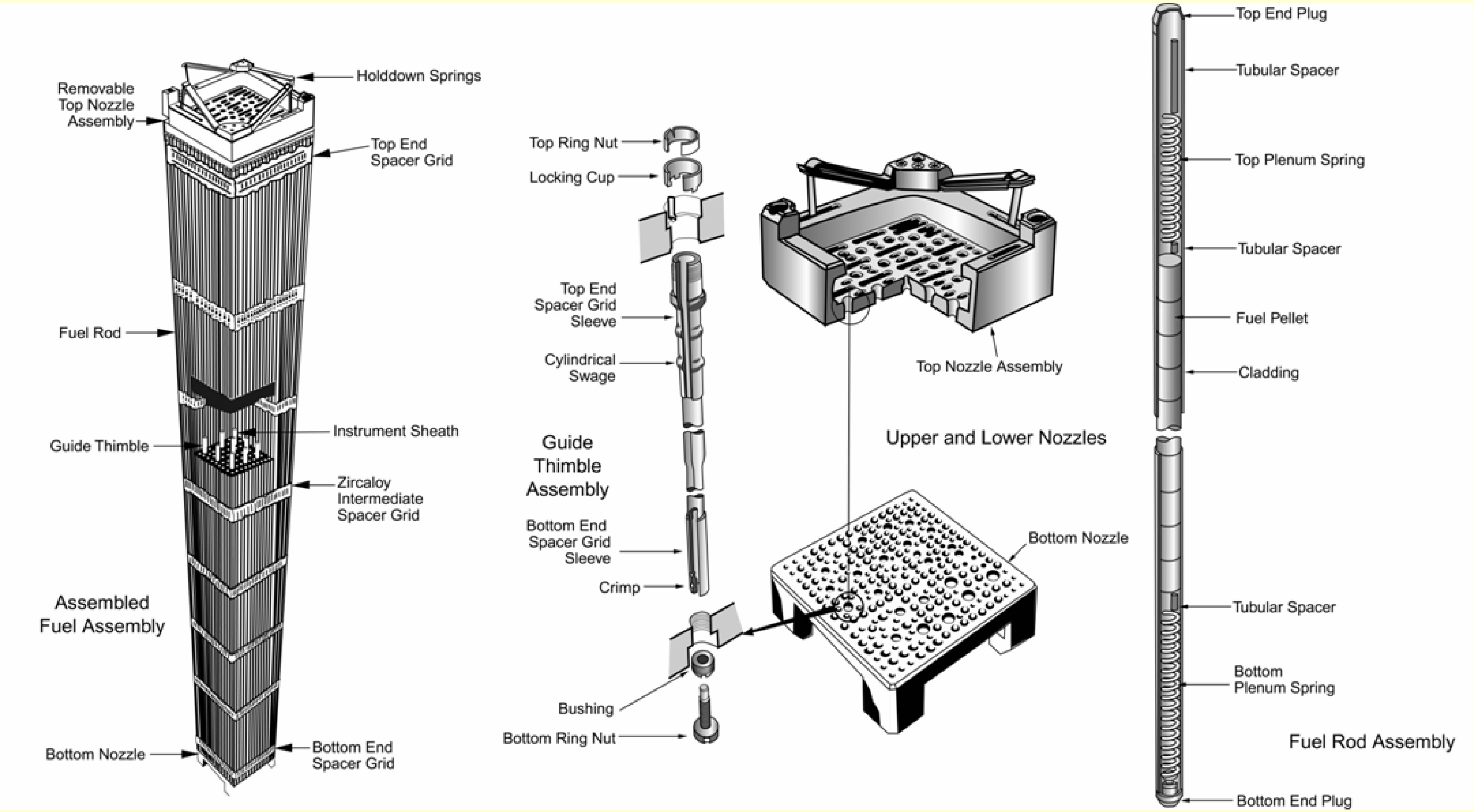
- Metal clad fuels: oxide and variants
  - Description and fabrication
  - Fuels for many reactors
    - Light-water reactors (LWRs)
      - Boiling Water Reactors (BWRs)
      - Pressurized Water Reactors (PWRs)
    - Fast Reactors cooled with Na, K, Bi, Pb, He
- Graphite-based fuels
  - Description of fuels and how they are fabricated
    - High-Temperature Gas-Cooled Reactors (HTGRs)
      - Also called Very-High-Temperature Reactors (VHTRs)
    - Pebble-Bed Modular (Gas Cooled) Reactor (PBMR)
- Spent fuel characteristics

Metal-Clad Fuels

Pressurized Water Reactor (PWR)

- Dimensions: square, H=4.1m, 21cm x 21 cm
- Weight: 460 kgU, 520 kg UO_2, 135 kg hardware
  - Hardware mostly Zircaloy (Zr with Sn, Fe, Cr)
  - Grid spacers: Zircaloy, Inconel, stainless steel
  - End pieces: Stainless steel, Inconel
- Fuel element array: 14 x 14 to 17 x 17
- Fuel element size: 1 cm OD, H=3.9m
- Enrichment: 3-5%
- May have separate burnable poison rods

Pressurized Water Reactor



Pressurized Water Reactor

Pressurized-Water
Fuel Assembly

Boiling Water Reactor (BWR)

- Dimensions: square, H=4.5m, 14 cm x 14 cm
- Weight: 180 kgU, 210 kg UO_2, 110 kg hardware
  - Hardware mostly Zircaloy (Zr with Sn, Fe, Cr)
  - Grid spacers: Zircaloy
  - Channel (aka shroud): Zircaloy
  - End pieces: Stainless steel
- Fuel element array: 8 x 8
- Fuel element size: 1.25 cm OD, H=4.1m
- Enrichment: 2.5-4.5%
- May have Gd in some rods and variable enrichment in 3-D

Boiling Water Reactor

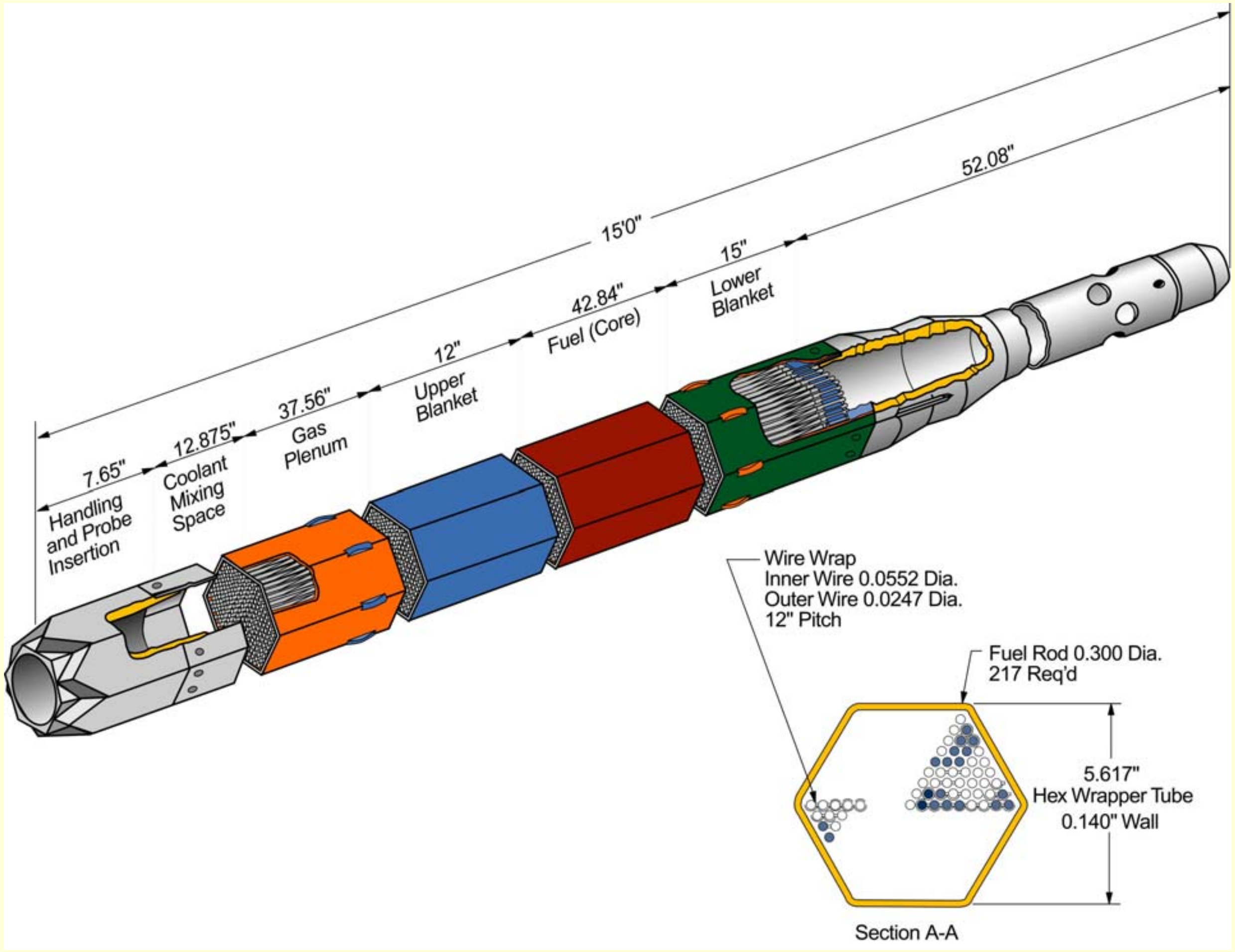
PWR and BWR Fuel Variants

- Advanced Cladding
  - Zirlo (Zr-Nb alloy) and Duplex (layered) for PWRs
  - Tweak Zircaloy composition for BWRs
- Moving to more smaller elements
- Mixed-oxide (MOX) fuel
  - U- 5-8% Pu
    - Already being done in US (weapons Pu) and elsewhere
  - Mixed actinides from advanced reprocessing
    - U-Np-Pu: modest extension of U-Pu fuel technology
    - Am-Cm: a challenge, probably requires targets
- More PWR fuel gradation and burnable poisons
- Thorium oxide fuel

Fast Breeder Reactor

- Dimensions: hexagonal, H=4-5.5m, W (flats)= 10-20 cm; HM height ~2m
- Weight: ~60 kgHM, ~65 kg MOX, ~135 kg hardware (core plus axial blanket)
  - Hardware: Stainless steel
  - Mostly wire wrap for pin spacing
- Fuel element array: 200-300 pins
- Fuel element size: 0.6-0.9 cm OD, H= 4-5m
- Enrichment: 15-30% Pu
- Blanket: All depleted UO_2
  - Fewer, larger diameter elements

Fast Reactor Fuel Assembly

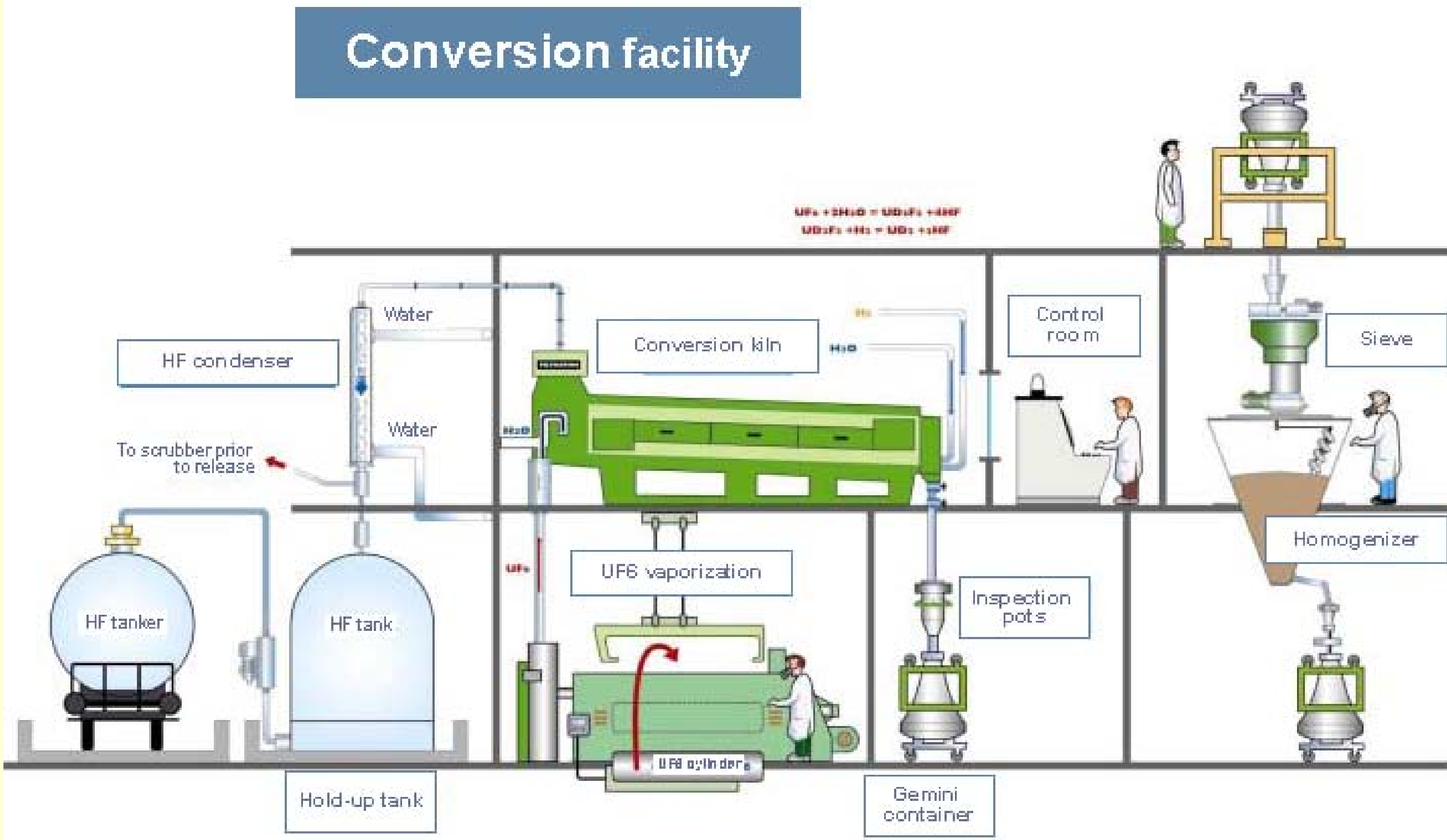


Fast Reactor Fuel Variants

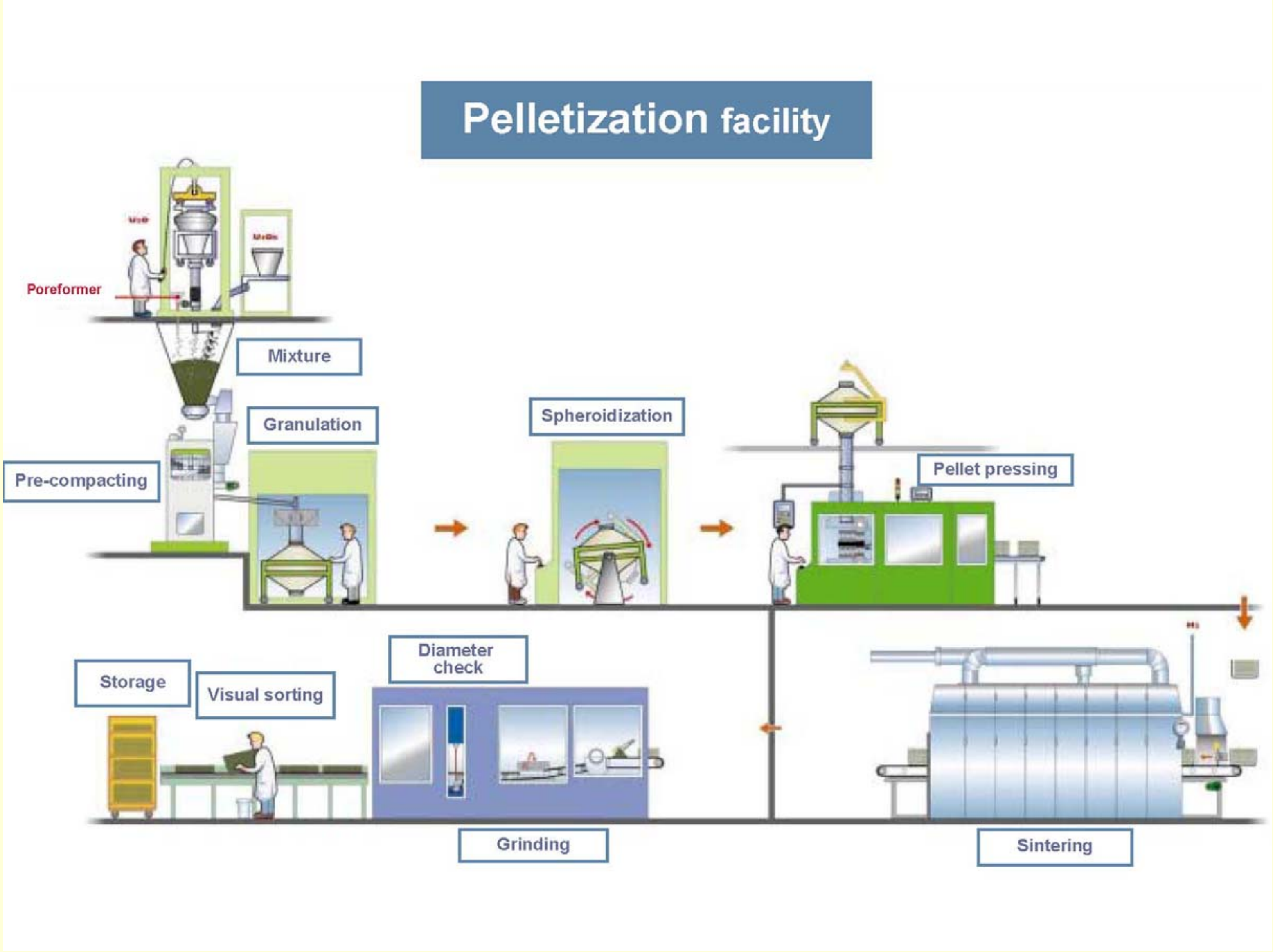
- Designs not settled: considerable variation in number of elements, dimensions, and weights possible
- Reduce breeding/conversion ratio to achieve net destruction of transuranics
  - Eliminate fertile blankets in favor of non-fertile neutron reflectors (e.g., stainless steel)
  - Inert matrix (e.g., ZrO_2) fuel
- Carbide, nitride, or metal fuel instead of oxide

Metal-Clad Fuel Fabrication

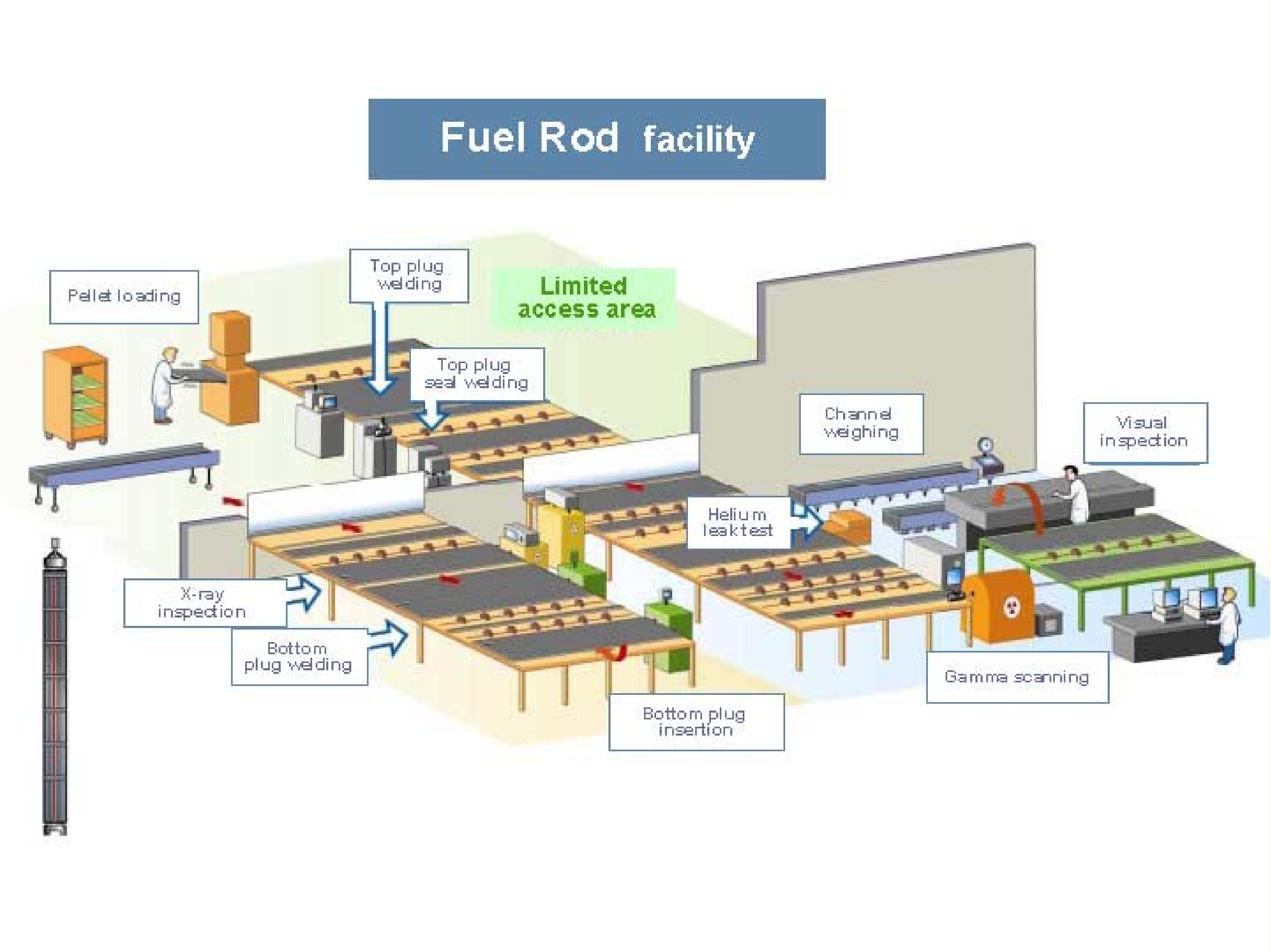
UO_2 Fuel Fabrication



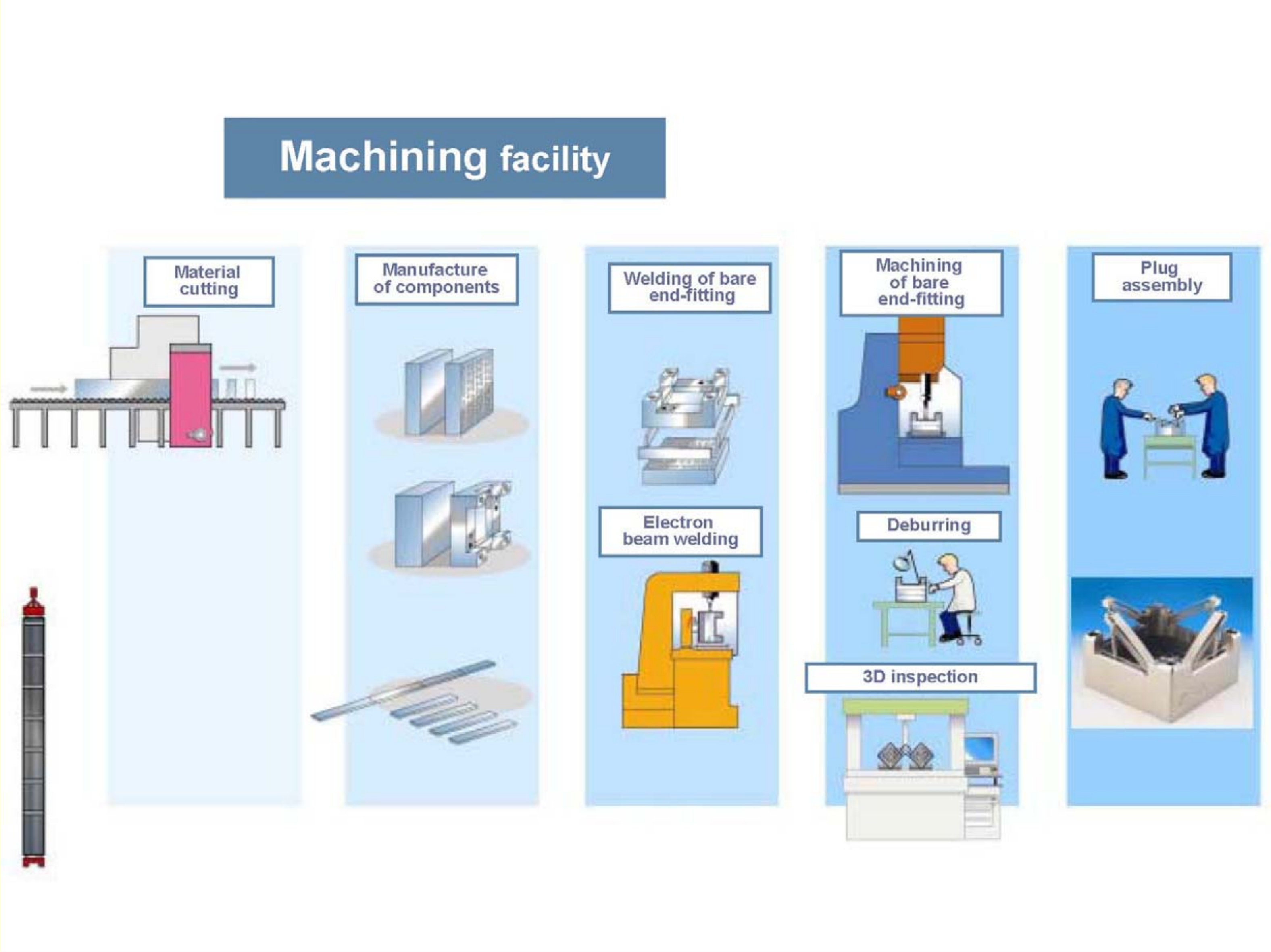
UO_2 Fuel Fabrication



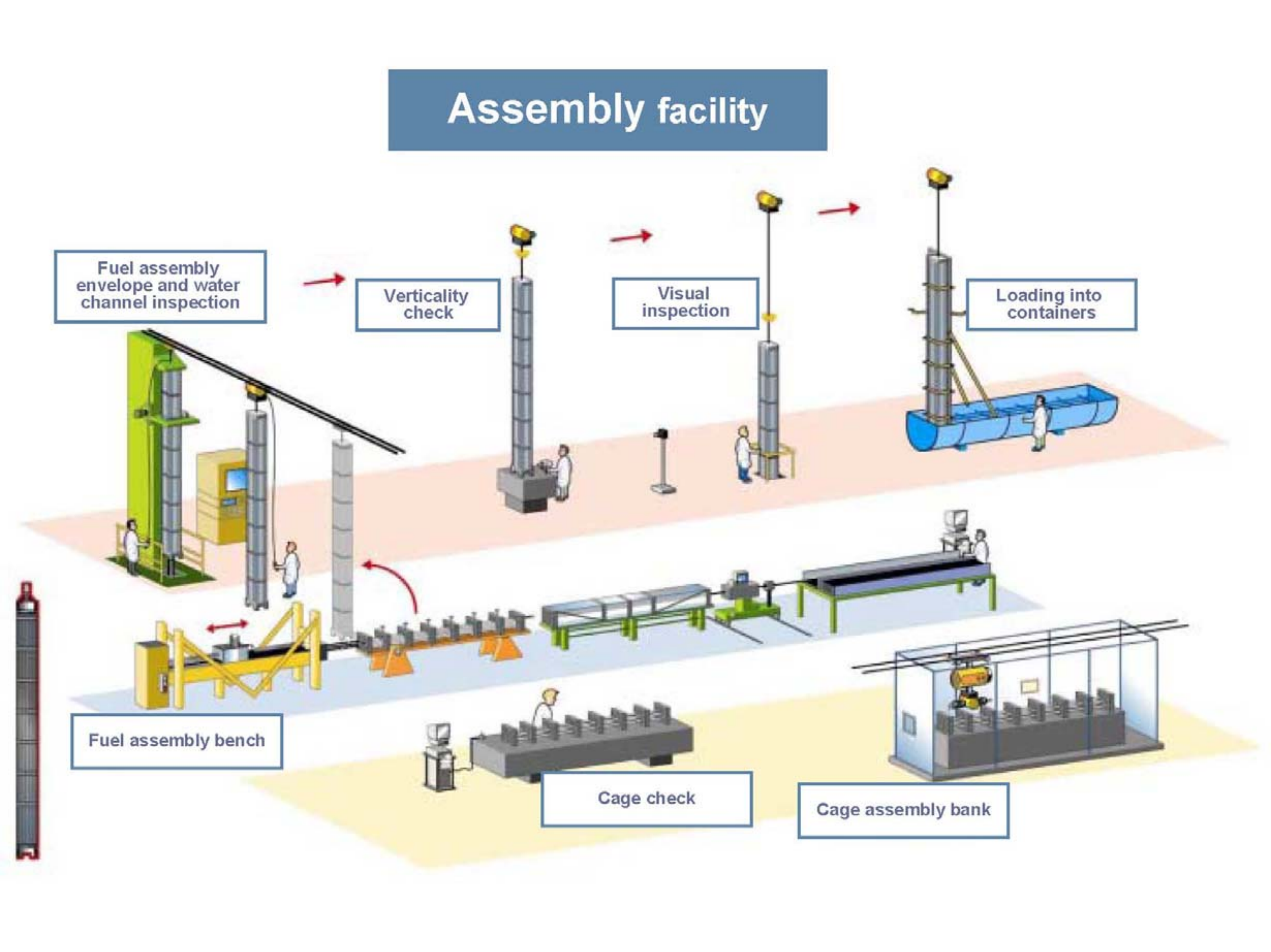
UO_2 Fuel Fabrication



UO_2 Fuel Fabrication



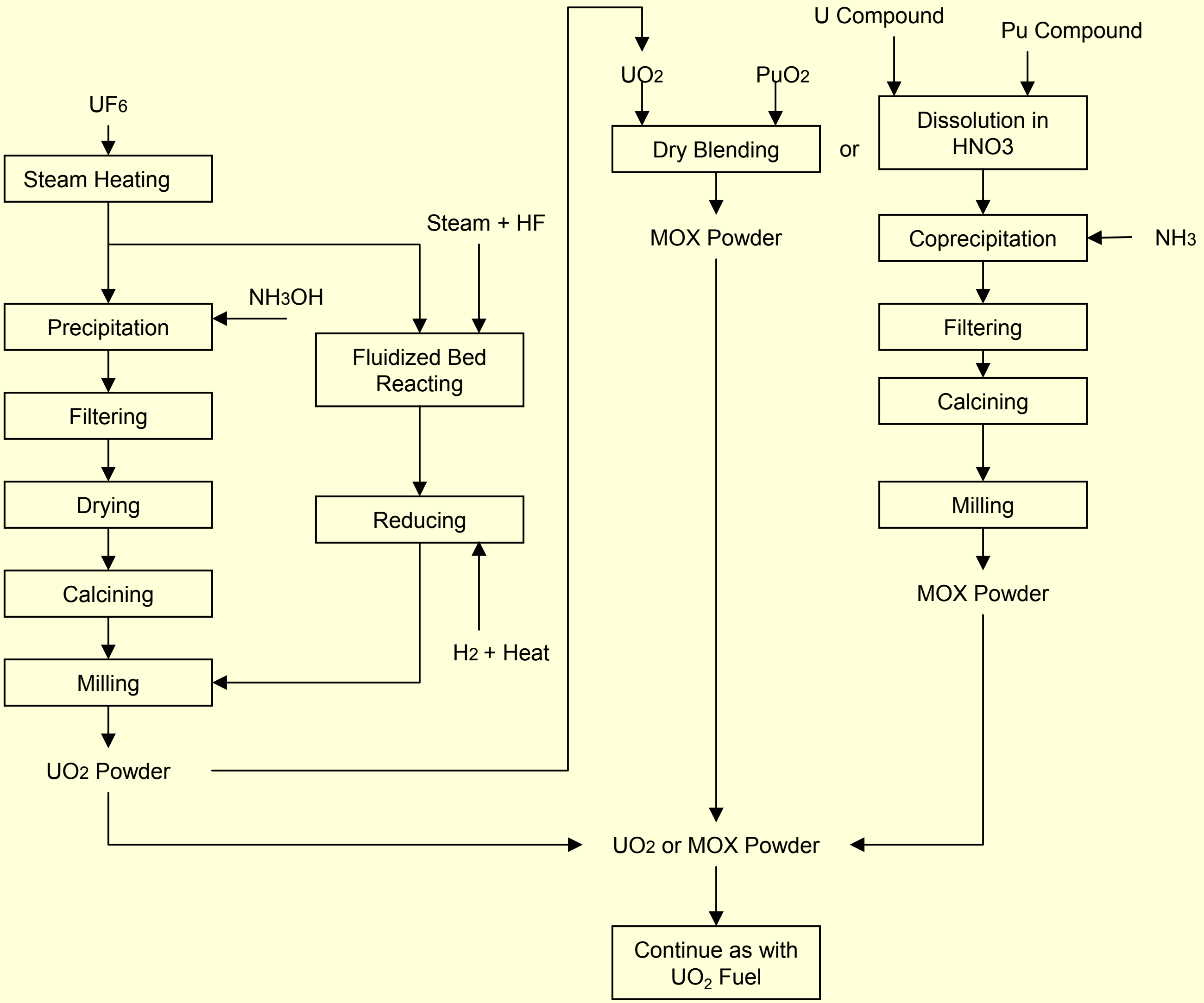
UO_2 Fuel Fabrication



MOX Fuel Fabrication

- The same as UO_2 fuel manufacture however….
  - Need to make sure the oxides are very homogenous and have required proportions
    - MOX fuel fabrication from powder usually dilutes a high-concentration “master blend” to the proper Pu enrichment
- Mixed-oxide (MOX): mixtures of actinide oxides
  - Conventionally, U-Pu
  - Advanced: U-Pu-Np, Am-Cm, combinations
- Conventional MOX fuels are being tested in the US but are currently being produced elsewhere
  - Facility using weapons Pu is being built at SRS

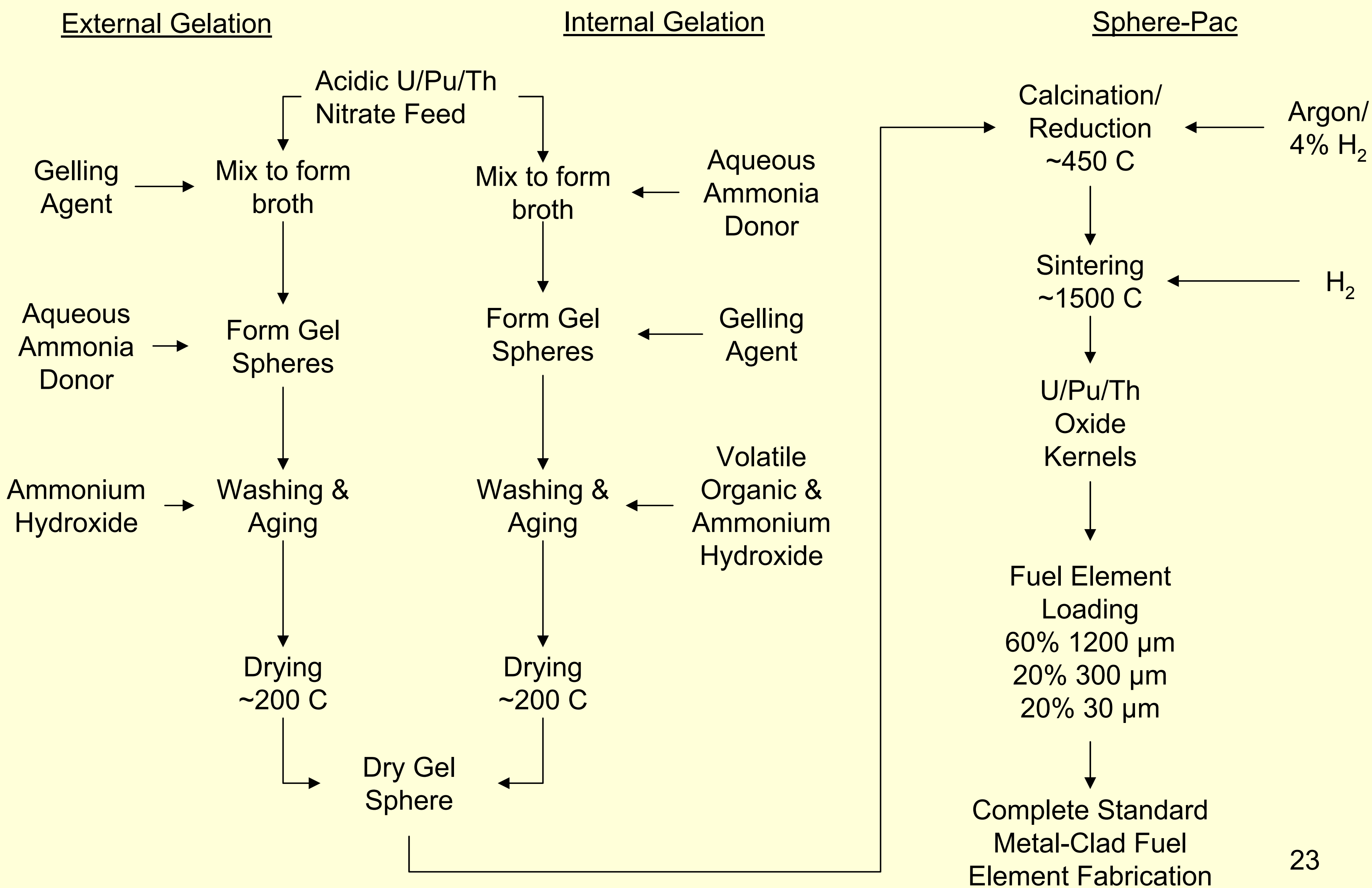
MOX Fuel Fabrication



Sol-Gel/Sphere-Pac Fabrication

- Used to prepare oxide fuels (U and MOX) without mixing powders, grinding, and dust
- Involves two steps:
  - Gelation: form kernels of U, Pu, and/or Th oxides by forming spheres
    - Based on ammonia precipitation of hydrated heavy metal oxides
    - 30, 300, and 1200μm optimal for Sphere-Pac (85% T.D.)
    - External gelation seems to be the current preference
  - Spheres are then washed and dried at ~200C
  - Sphere-Pac: Calcine and then sinter the spheres and load them into clad tubes

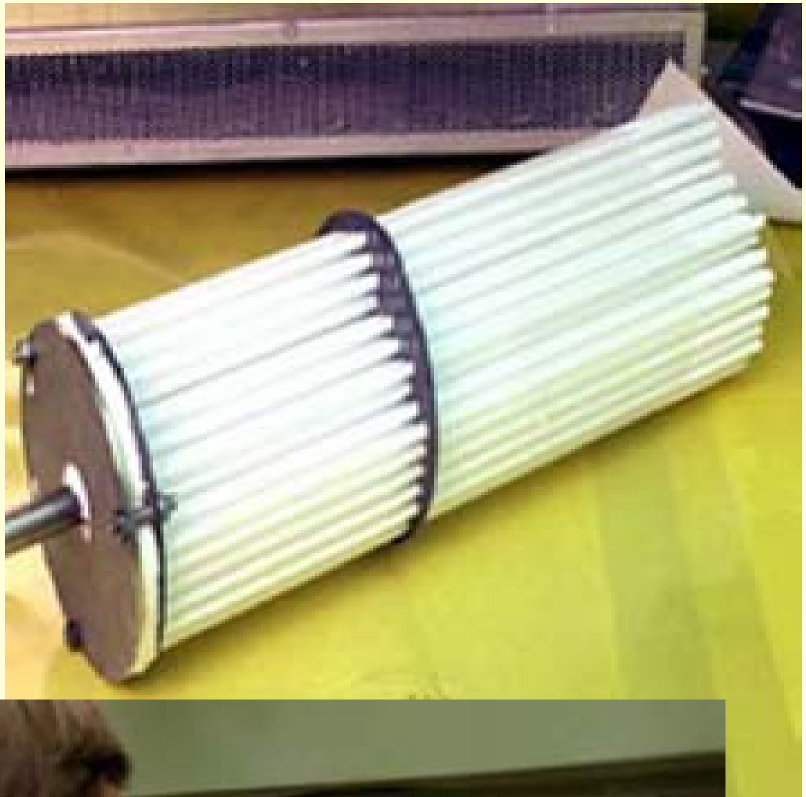
Sol-Gel/Sphere-Pac Fabrication



Metal Fuel Fabrication

- Begin with a furnace containing a molten mixture of actinides, some fission products, and alloying constituents
- Make a mold having an array of quartz tubes
- Insert mold in furnace, seal, and evacuate
- Lower mold into melt and increase pressure to force metal melt into tubes
- Raise mold, cool, break to yield metal fuel “pellets” ~0.5m long.
- Insert in metal clad as with oxide fuels

Metal Fuel Fabrication



Fabrication Scrap Recycle

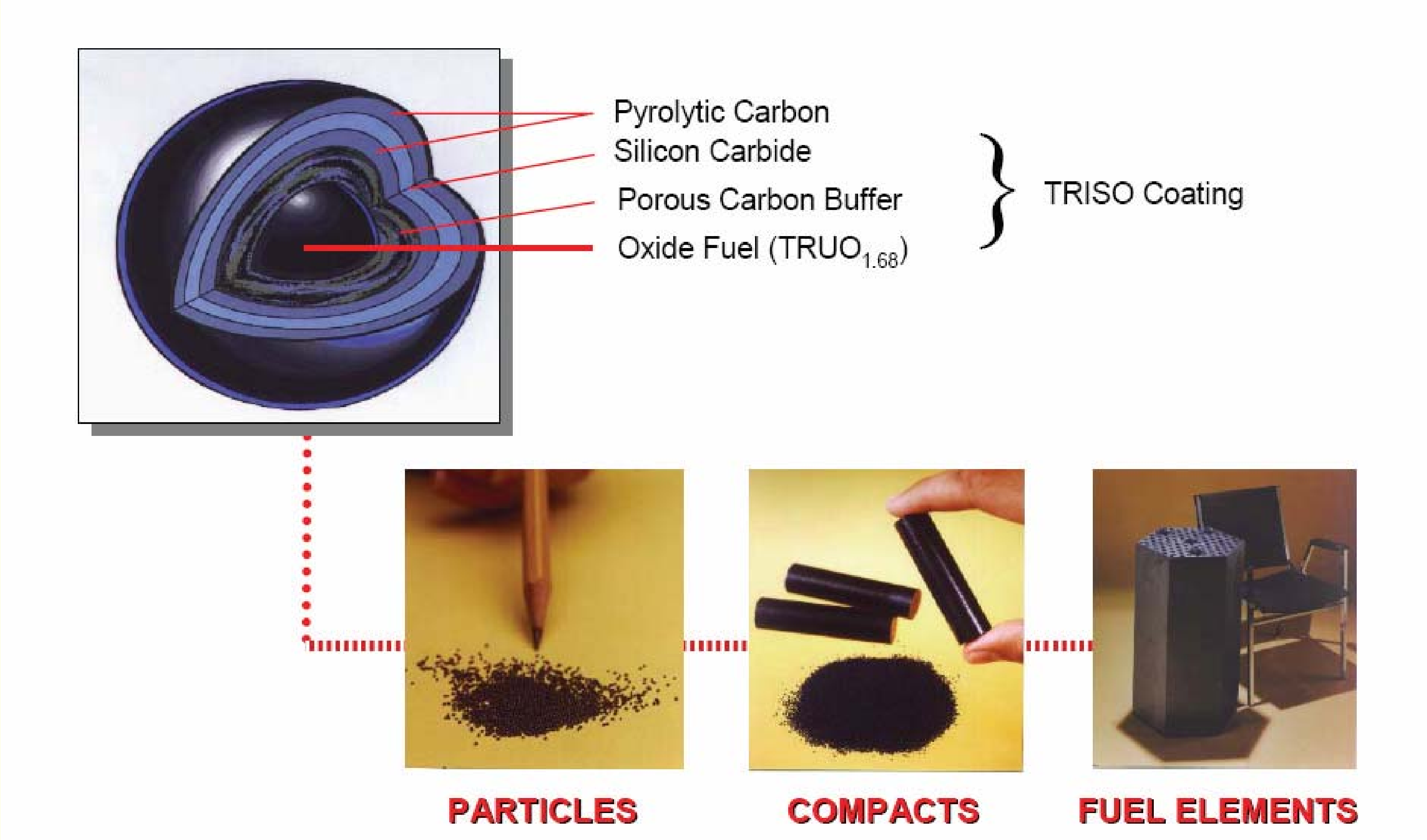
- All fabrication processes internally recycle off-specification fuel
  - Essentially dissolution and U/Pu/MOX purification steps used in a reprocessing plant
  - Off-spec metal fuels simply go back into the melt furnace or electrorefiner

Graphite-Based Fuels

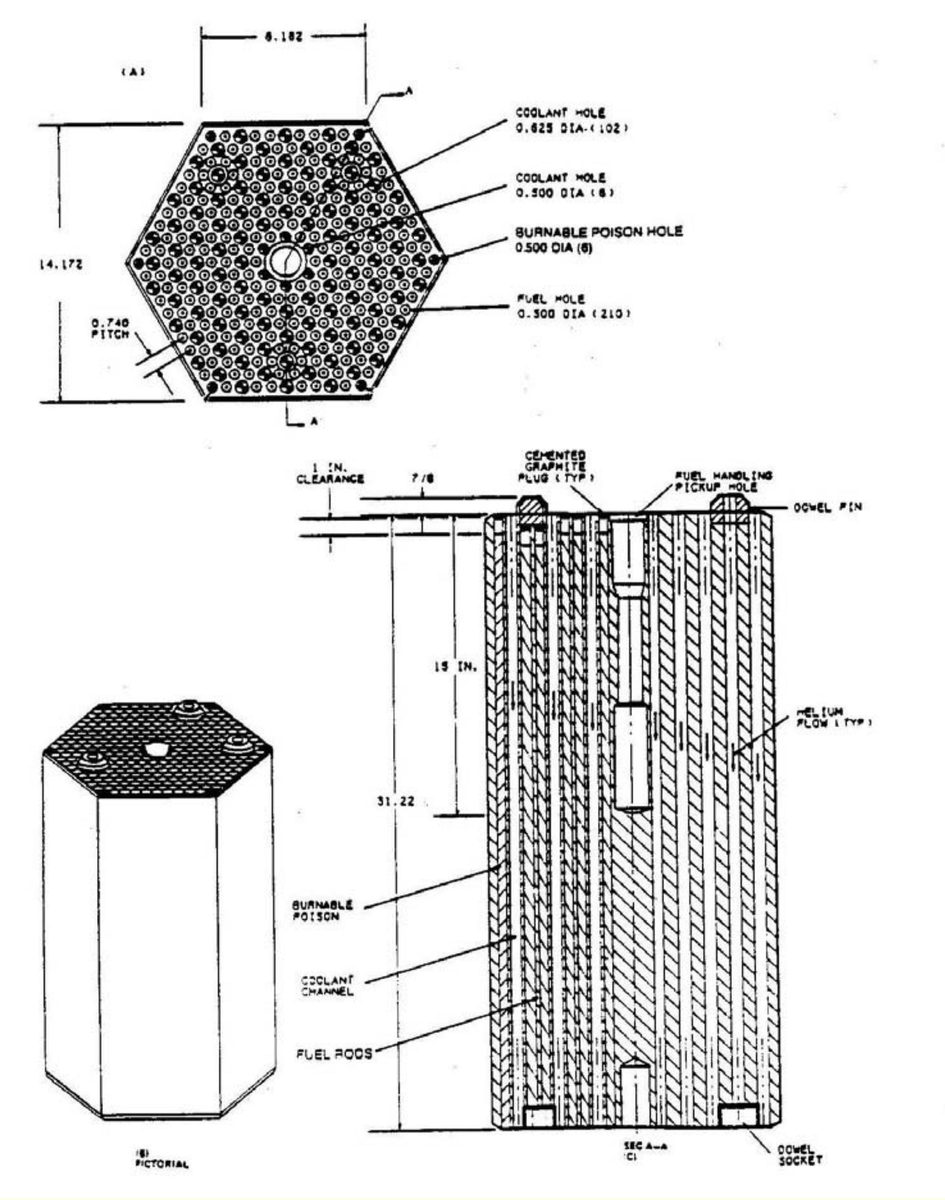
HTGR Prismatic Fuel

- Dimensions: hexagonal, H=0.8m, 0.36m (flats)
- Weight: 5-7 kgU, 5.5-7.5 kg UO_2
  - Hardware 126 kg C (mostly graphite), 4 kg SiC
- ~1000 blocks for 600 MW(t) reactor
- Fuel element array: 210 on a triangular pitch
  - 108 Coolant channels
- Fuel element size: 1.3 cm OD, H=0.8m
  - Contains 14-15 “compacts” with 350-500μm TRISO particles
- Enrichment: 8-20%
- May have separate B_4C burnable poison rods

HTGR Prismatic Fuel



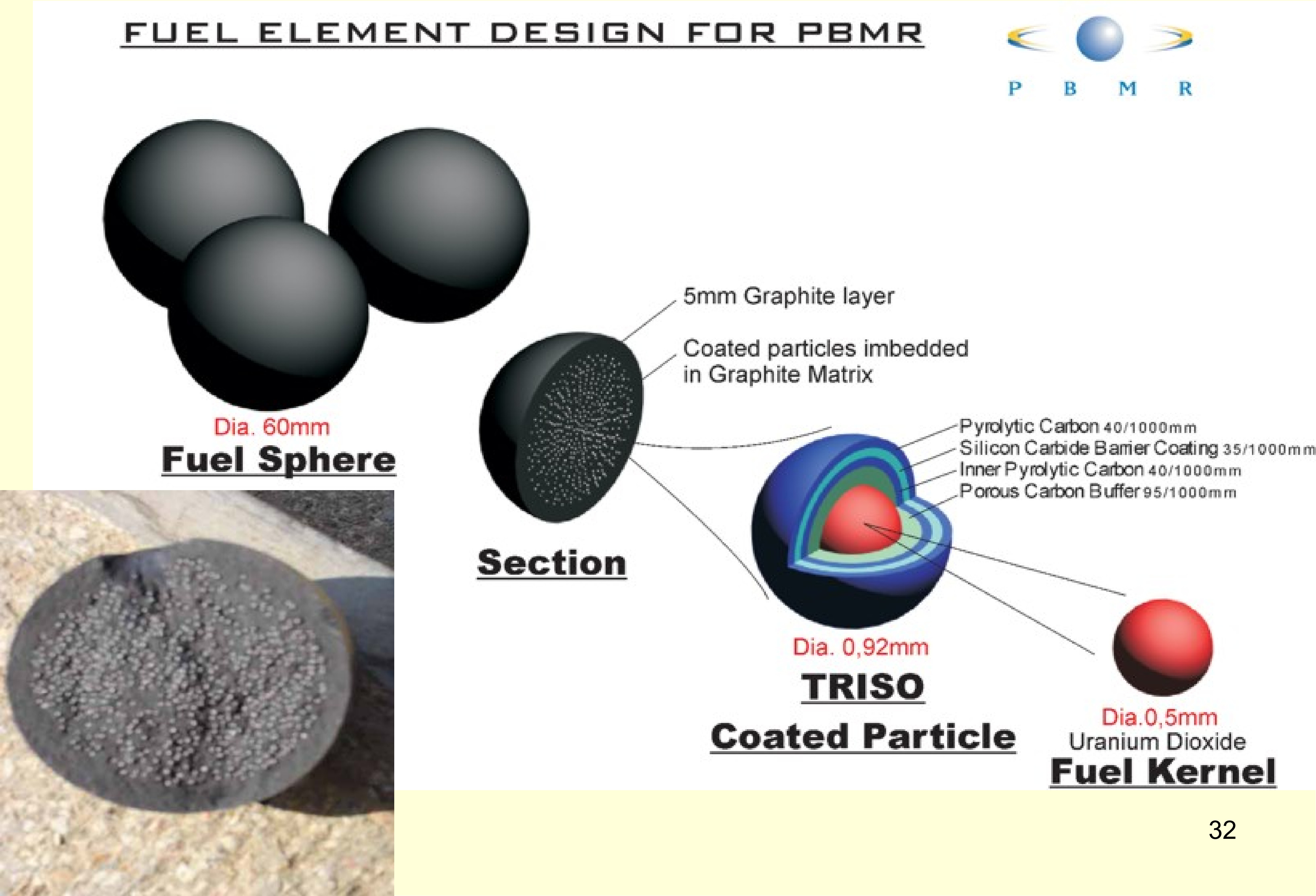
HTGR Prismatic Fuel



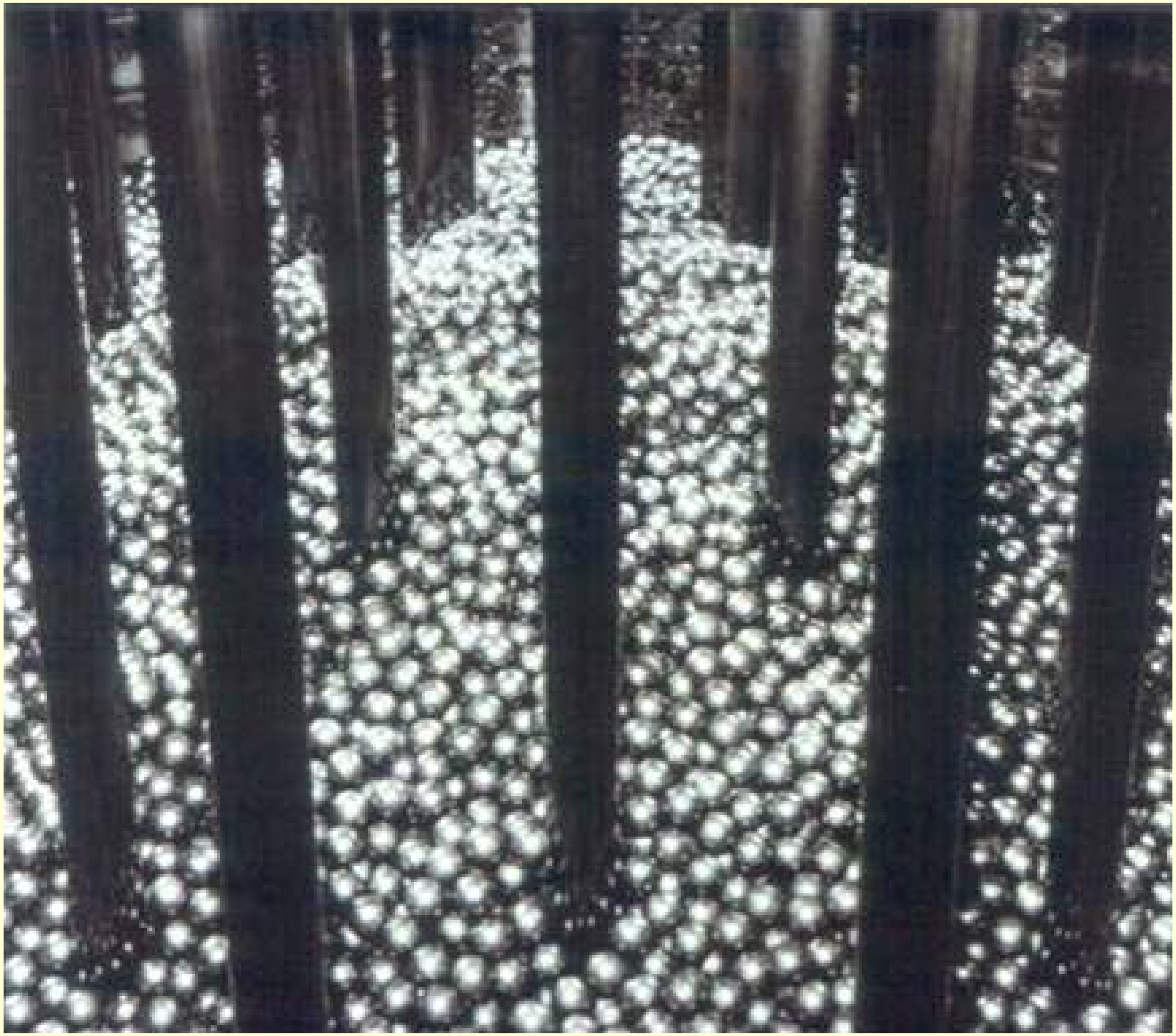
Pebble Bed Reactor Fuel

- Dimensions: Spherical, D= 6.0 cm
- Weight: 9 g U, 10 g UO_2
  - "Hardware" 194 g C (mostly graphite), ~6 g SiC
- ~360,000 pebbles for 400 MW(t) reactor
- Fuel element array: random pile
- Fuel element size:
  - 900μm TRISO particle
  - ~15,000 particles per pebble
- Enrichment: 7-10%

Pebble Bed Reactor Fuel

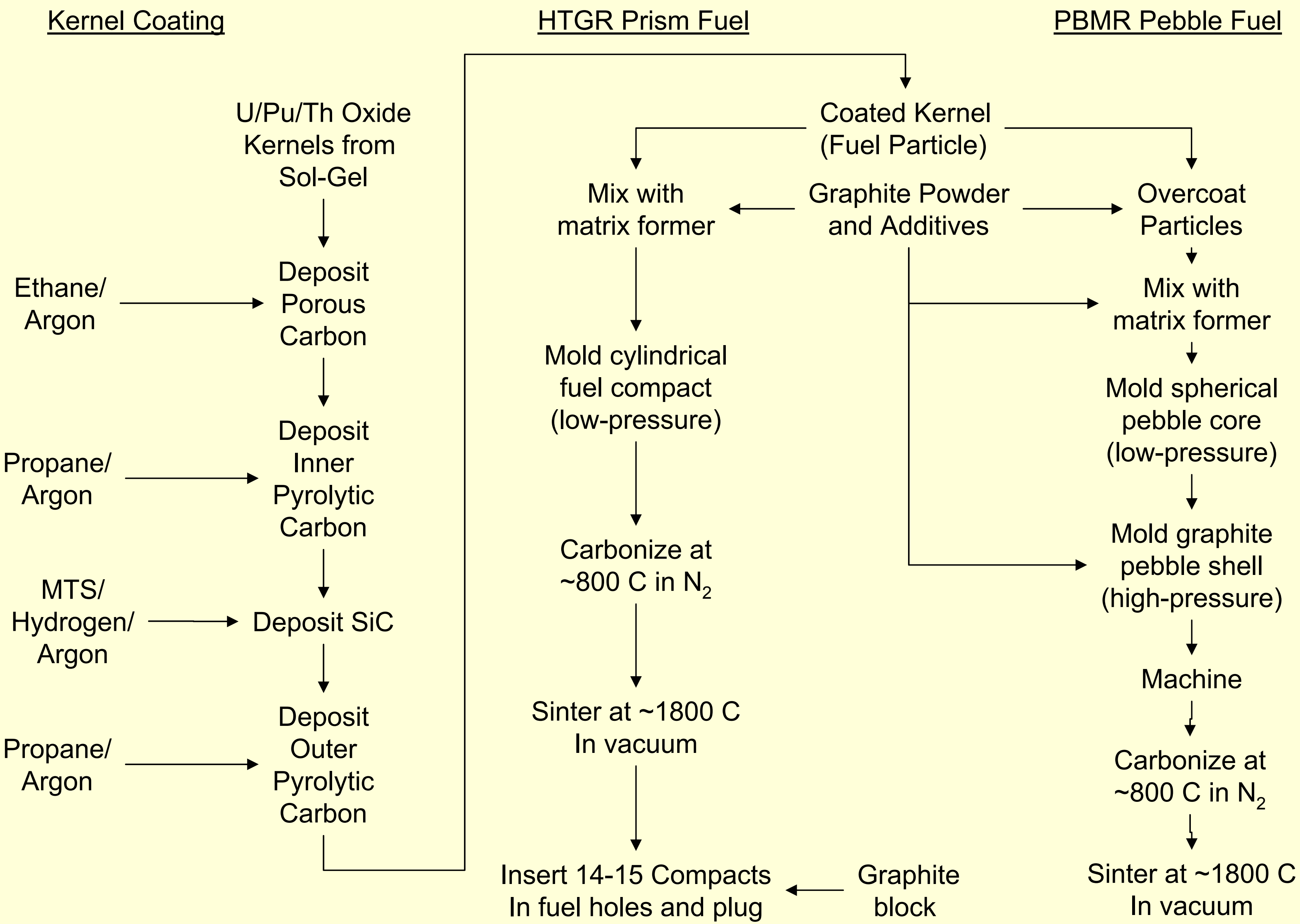


Pebble Bed Reactor



Graphite Fuel Fabrication

Graphite Fuel Fabrication



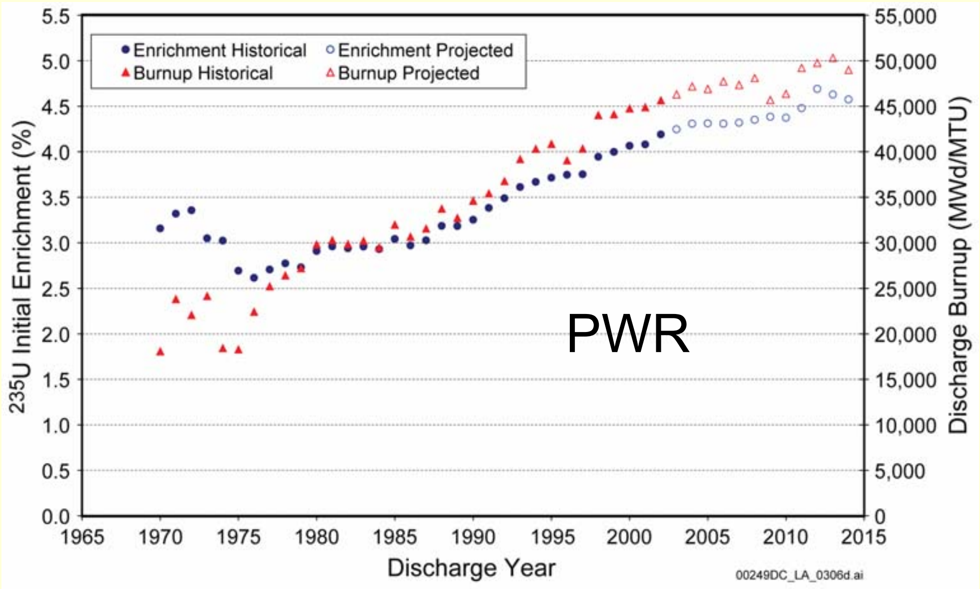
Spent Fuel Characteristics

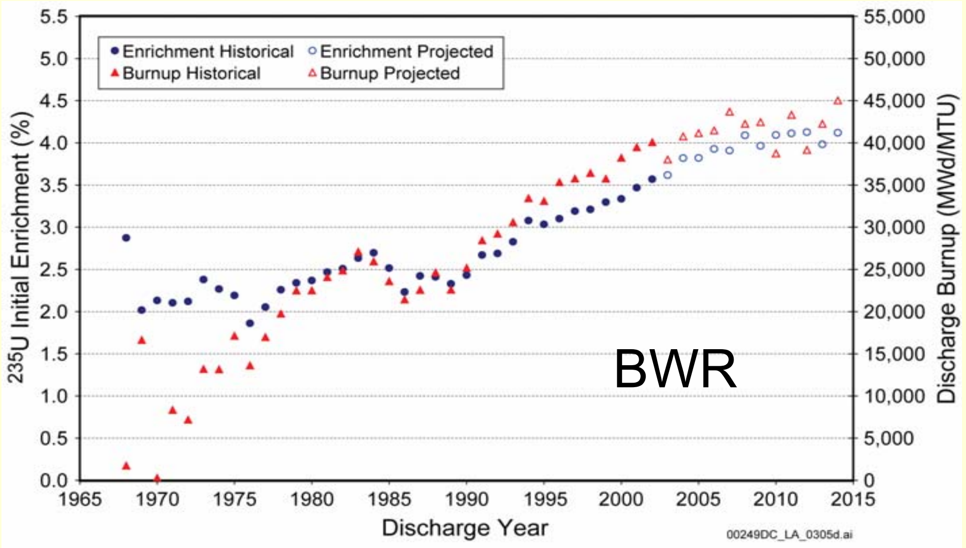
Effects of Neutron Irradiation

- Elemental and isotopic composition changes
  - Actinides fission to produce energy
    - Rule-of-thumb: Fissioning 1% of actinides = 10 GWd/MT
    - Fission Products produced in amounts equal to actinides destroyed
  - Irradiation produces neutron capture products
    - Actinides: U-236, Np, Pu, Am, Cm, U-233
    - Hardware and fuel matrix: Activation products
      - Major constituents yield ^{93}Zr, ^{60}Co, etc.
      - Important trace contaminants: U (transuranics), Li (^{3}H), N (^{14}C)
- Physical changes: fuel swelling/cracking, clad embrittlement, fission gas release to plenum

How much burnup?

- PWRs/BWRs
  - Now 40-50 GWd/MTHM
  - Climbing but enrichment challenges
- Fast reactors
  - Hope for 100+ GWd/MTHM
- Graphite-fueled reactors
  - Hope for 100+ GWd/MTHM

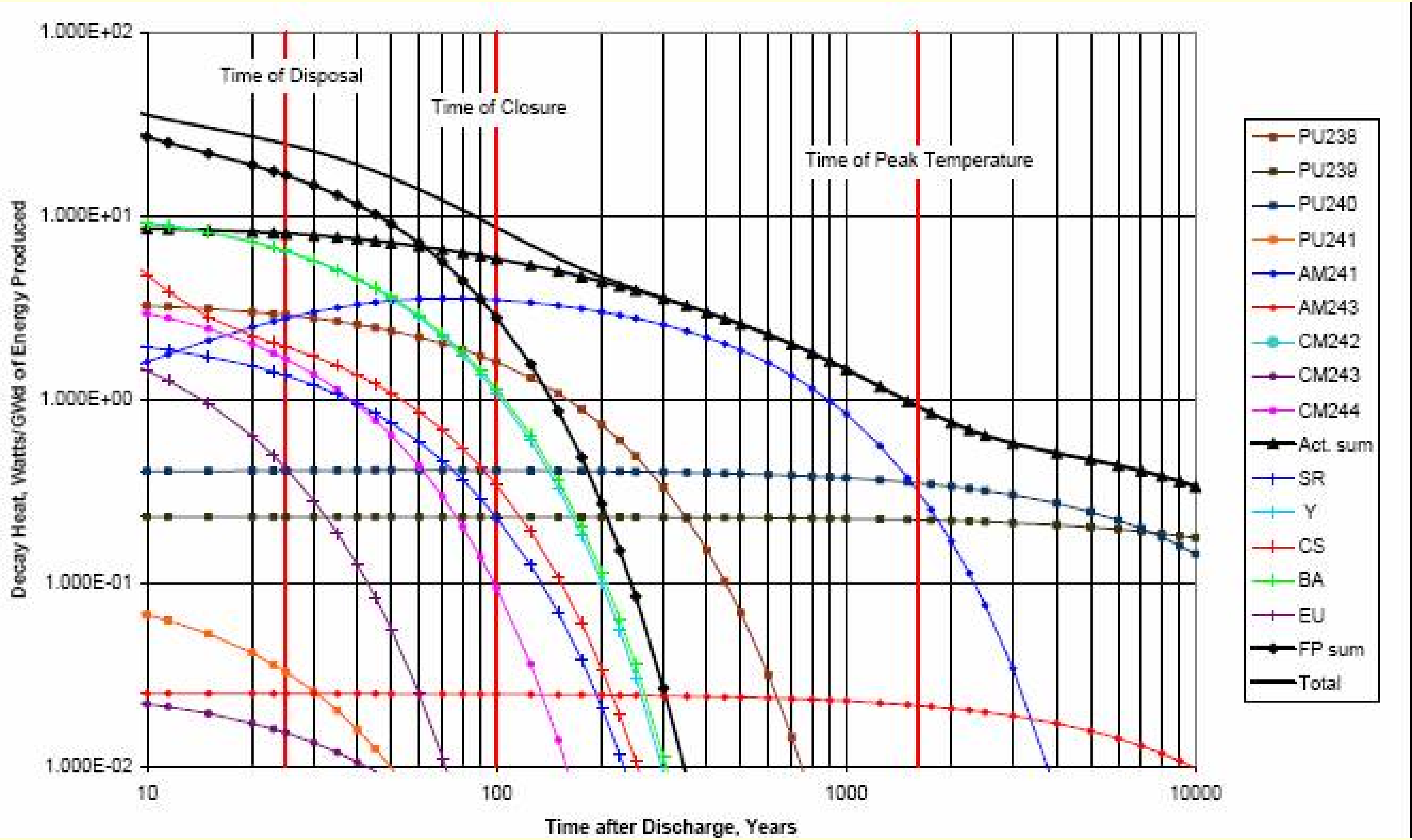




What are the impacts?

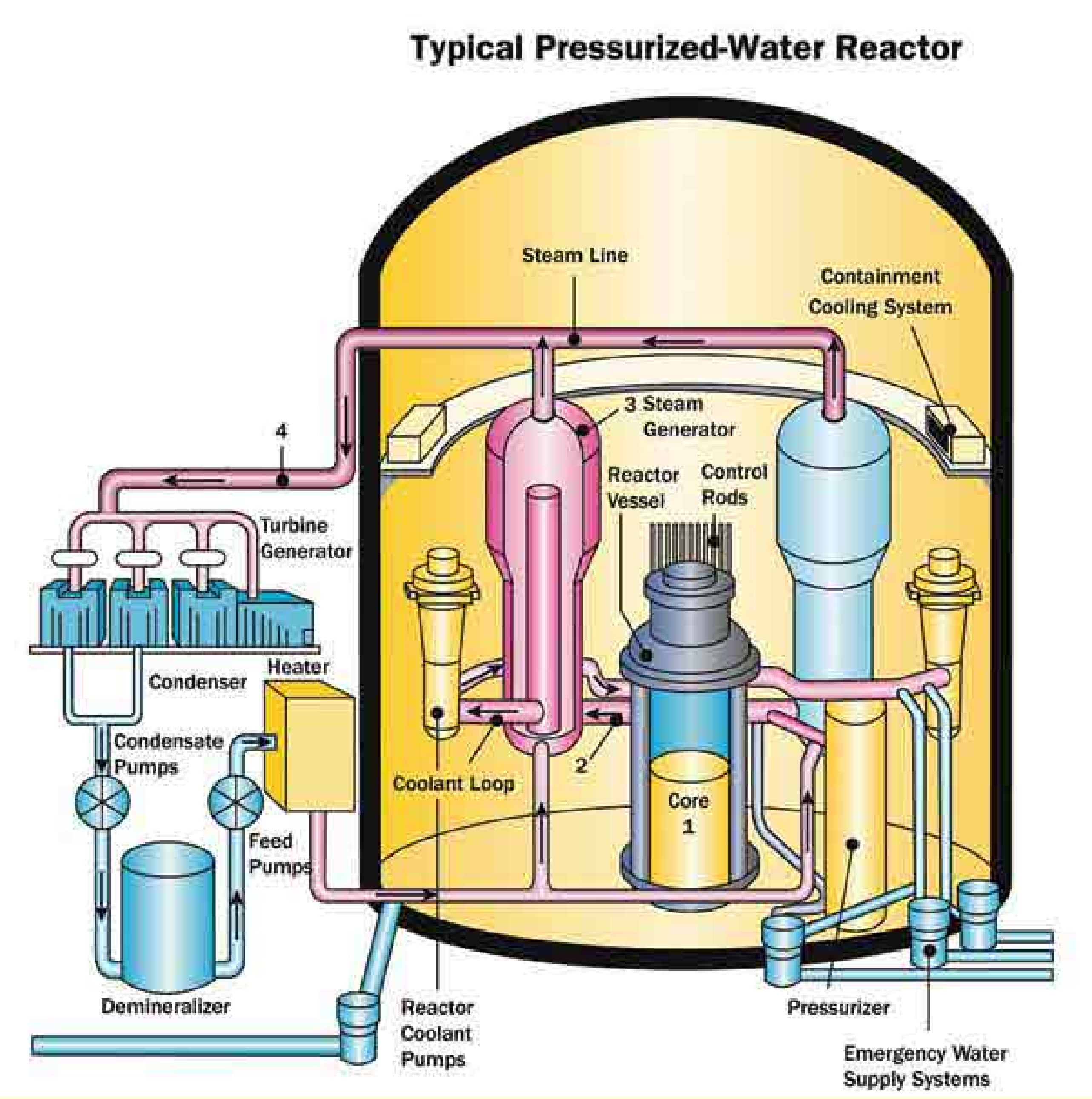
- Complex mix of elements to be considered in separations (~entire periodic table)
- Greatly increased radioactivity
  - Gamma-rays/x-rays
  - Neutrons: spontaneous fission and (α,n)
  - Alpha (helium nucleus)
  - Beta (electron)
- Impacts
  - Penetrating radiation → need radiation shielding
  - Particles → material damage
  - Decay heat → provisions for heat removal

Decay Heat, PWR, 33 GWd/MT

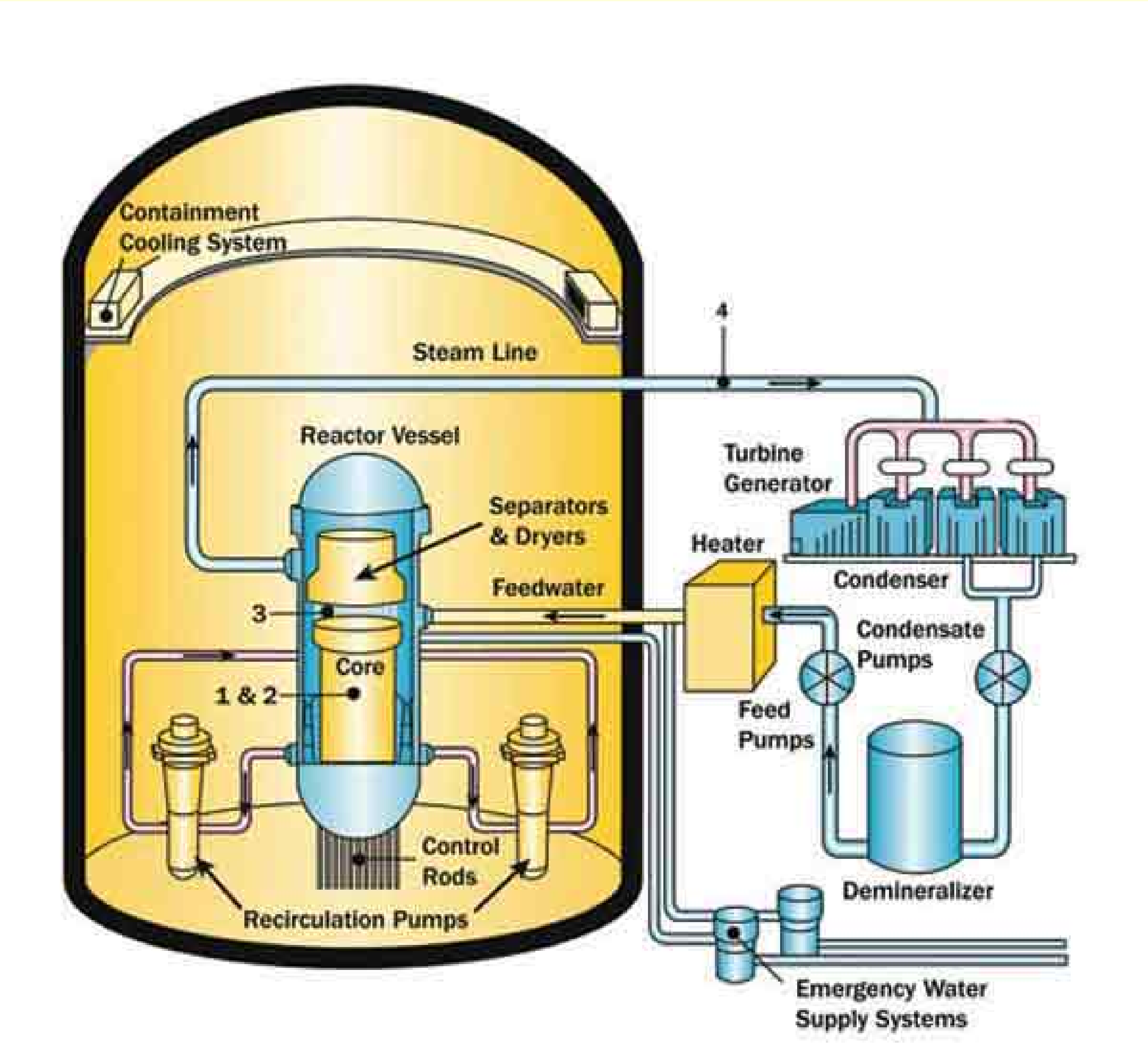


Backup Slides

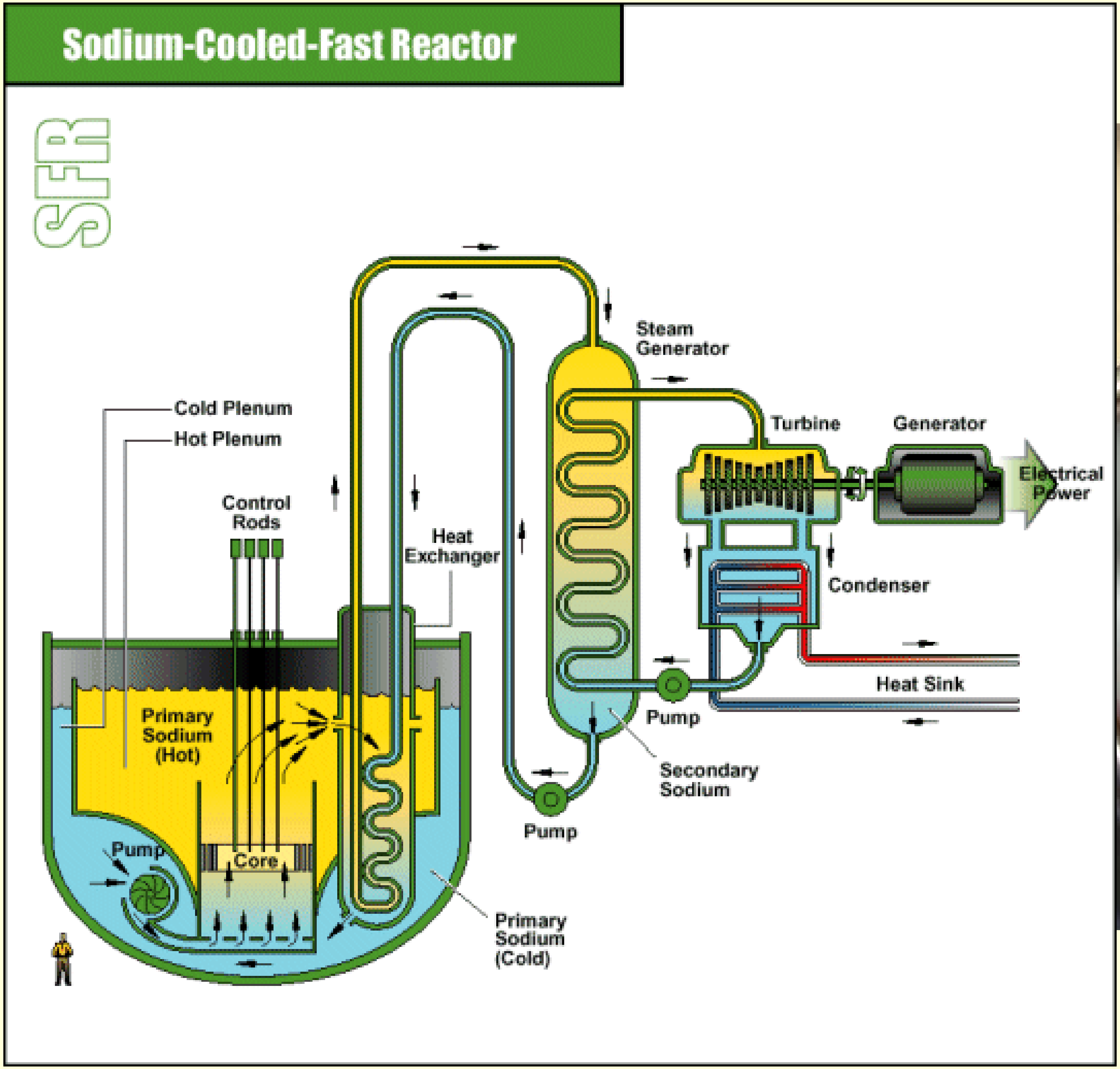
Pressurized Water Reactor



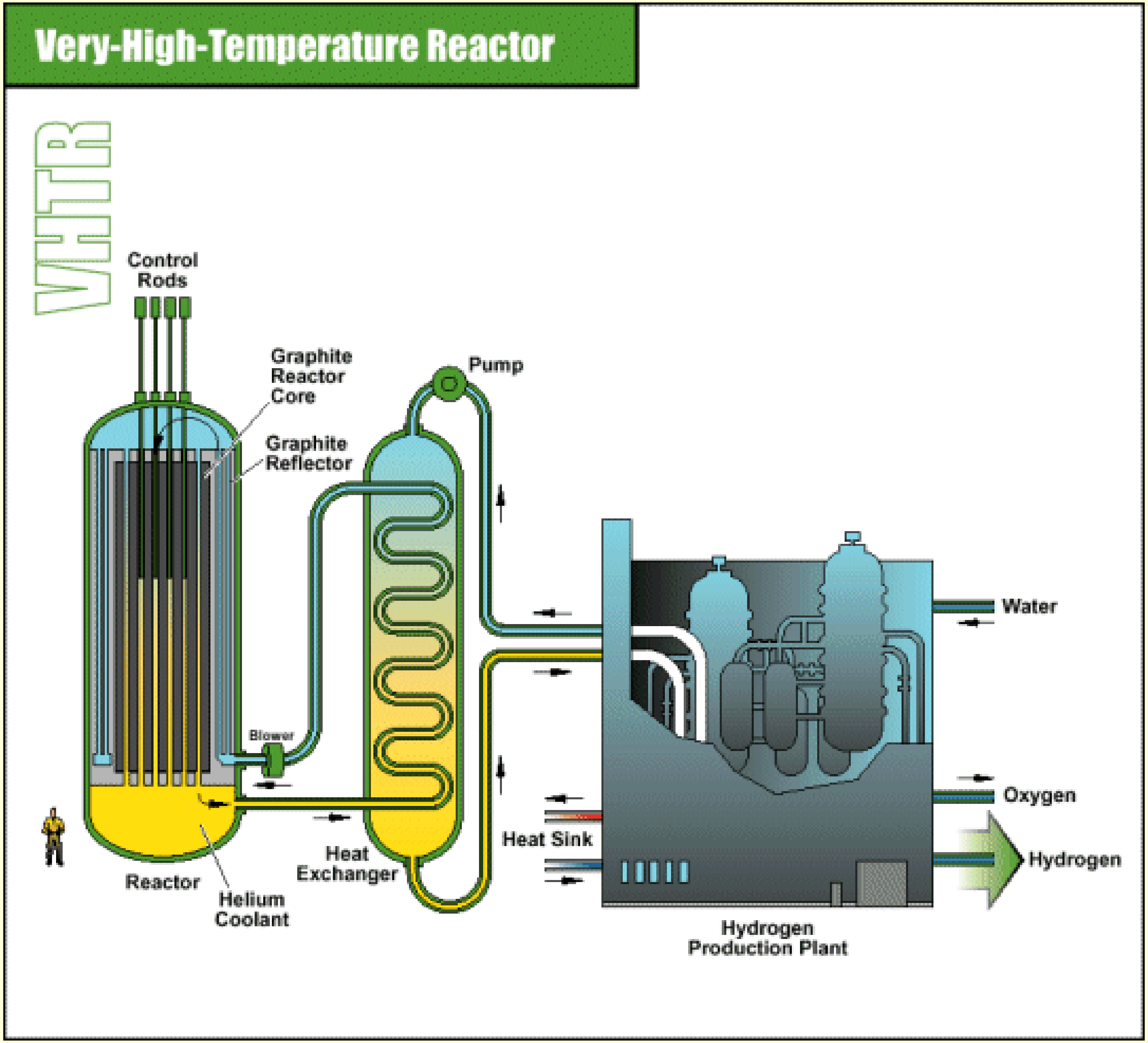
Boiling Water Reactor



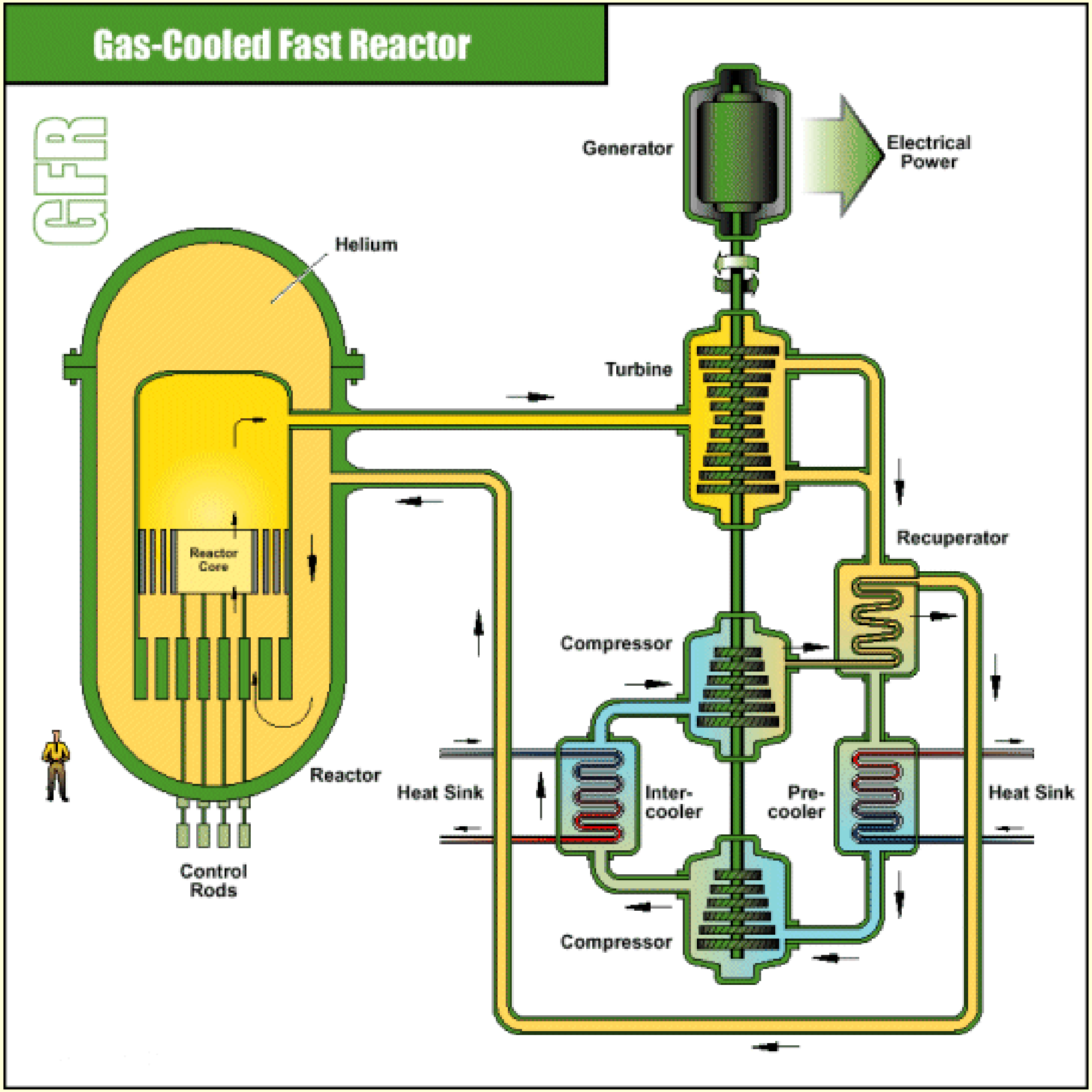
Sodium-Cooled Fast Reactor



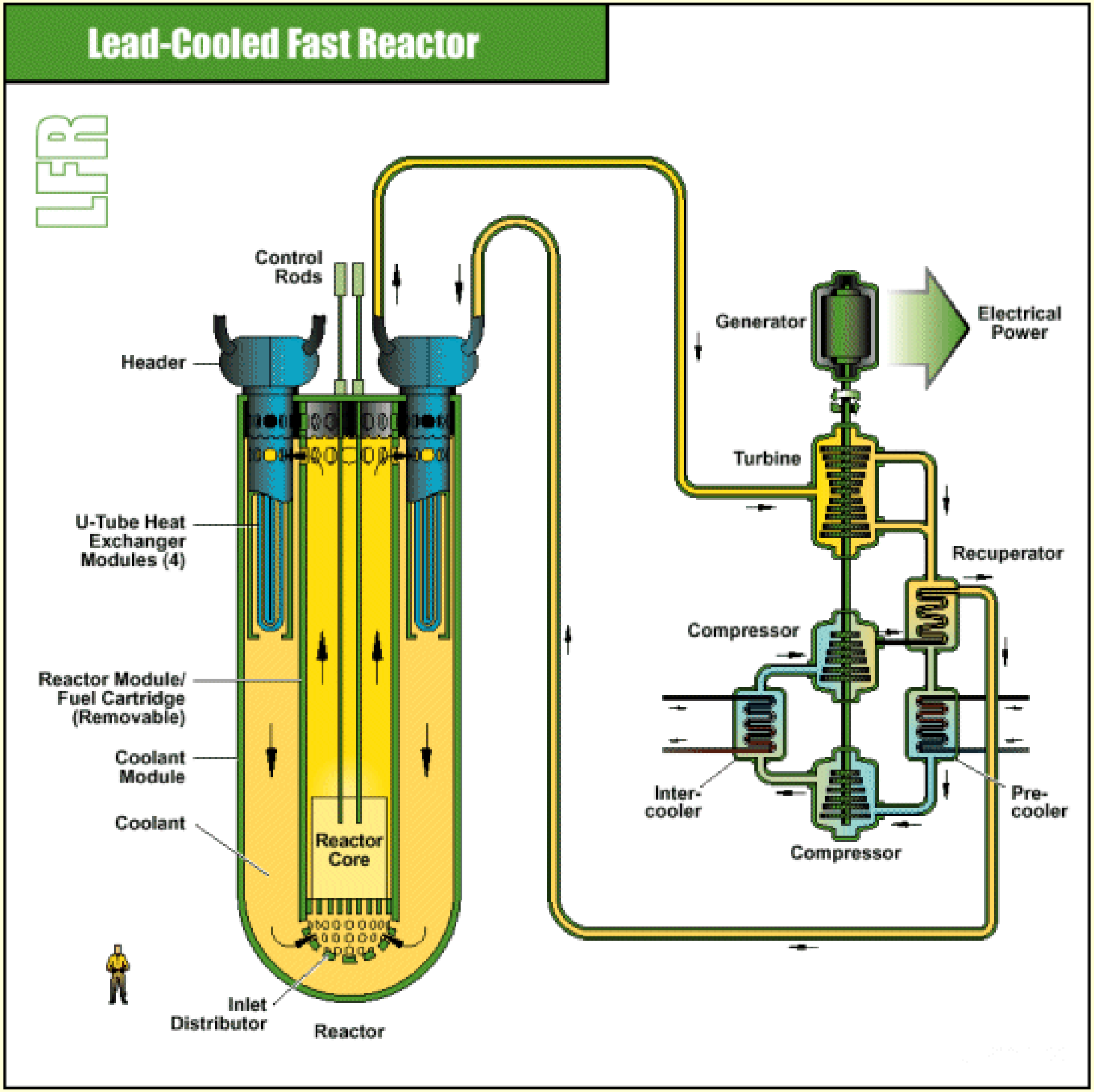
Very-High-Temperature Reactor



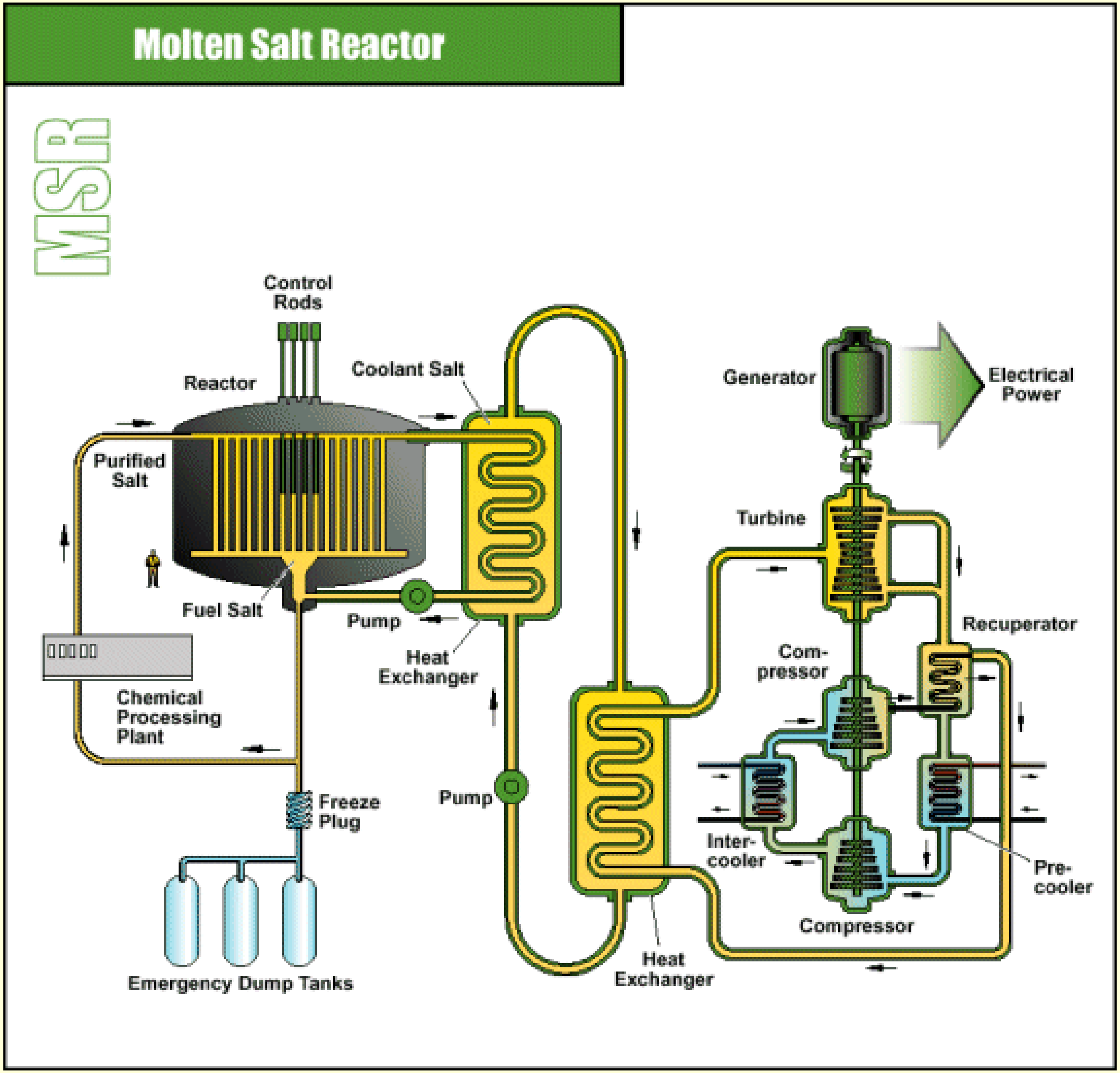
Gas-Cooled Fast Reactor



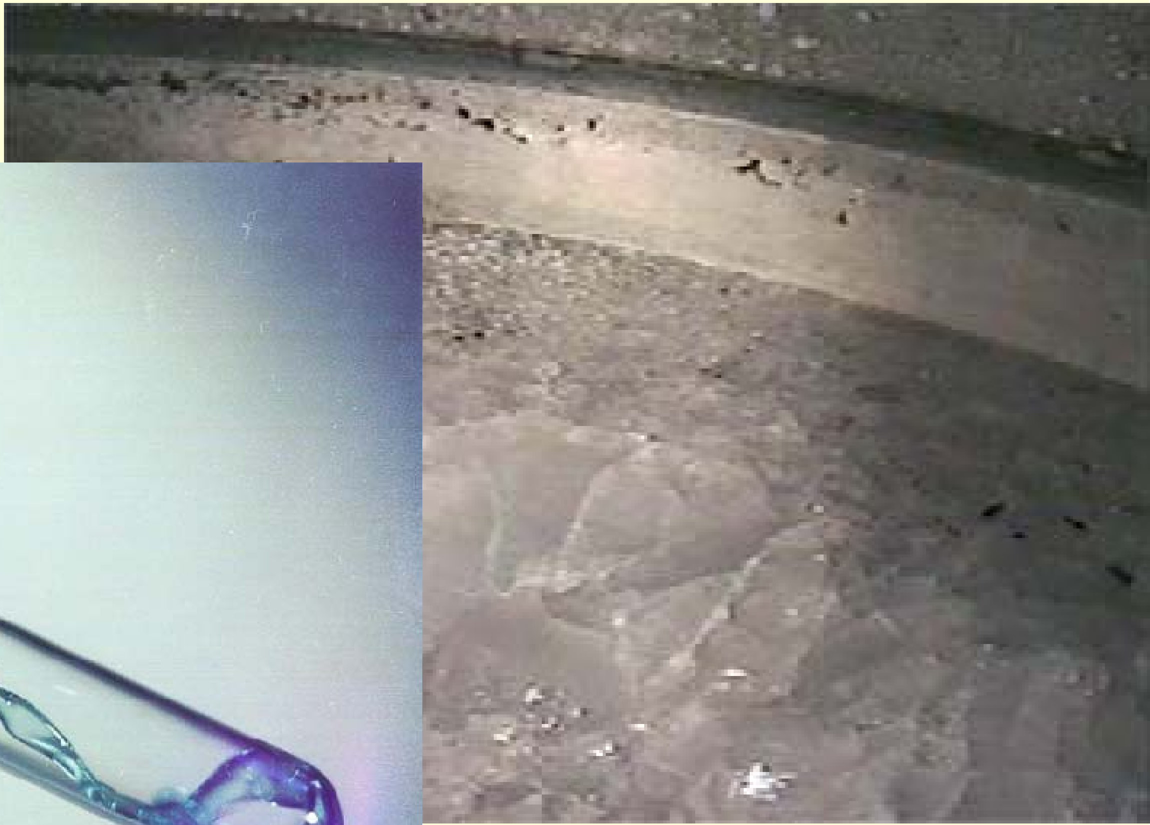
Lead-Cooled Fast Reactor



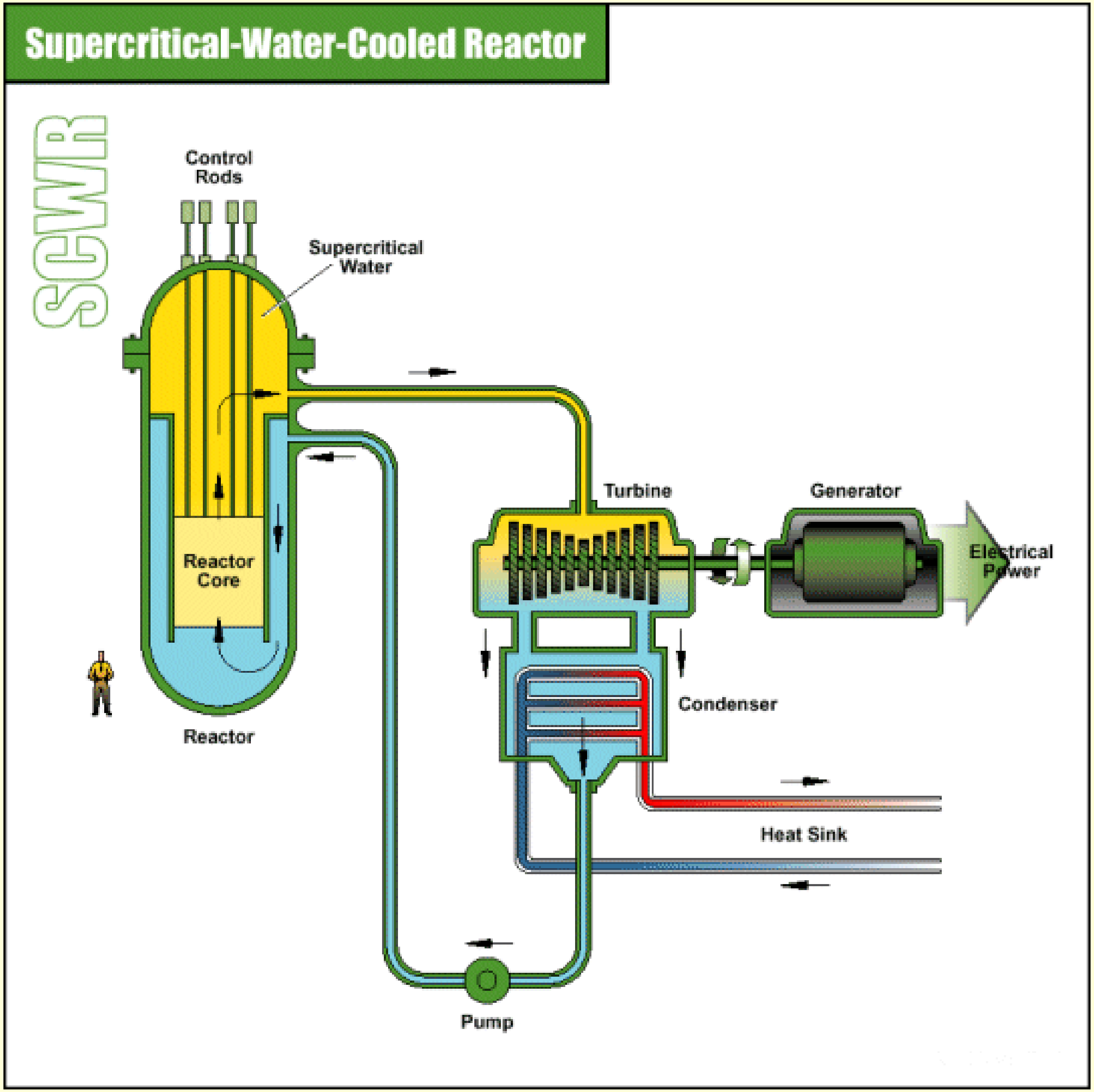
Molten Salt Reactor



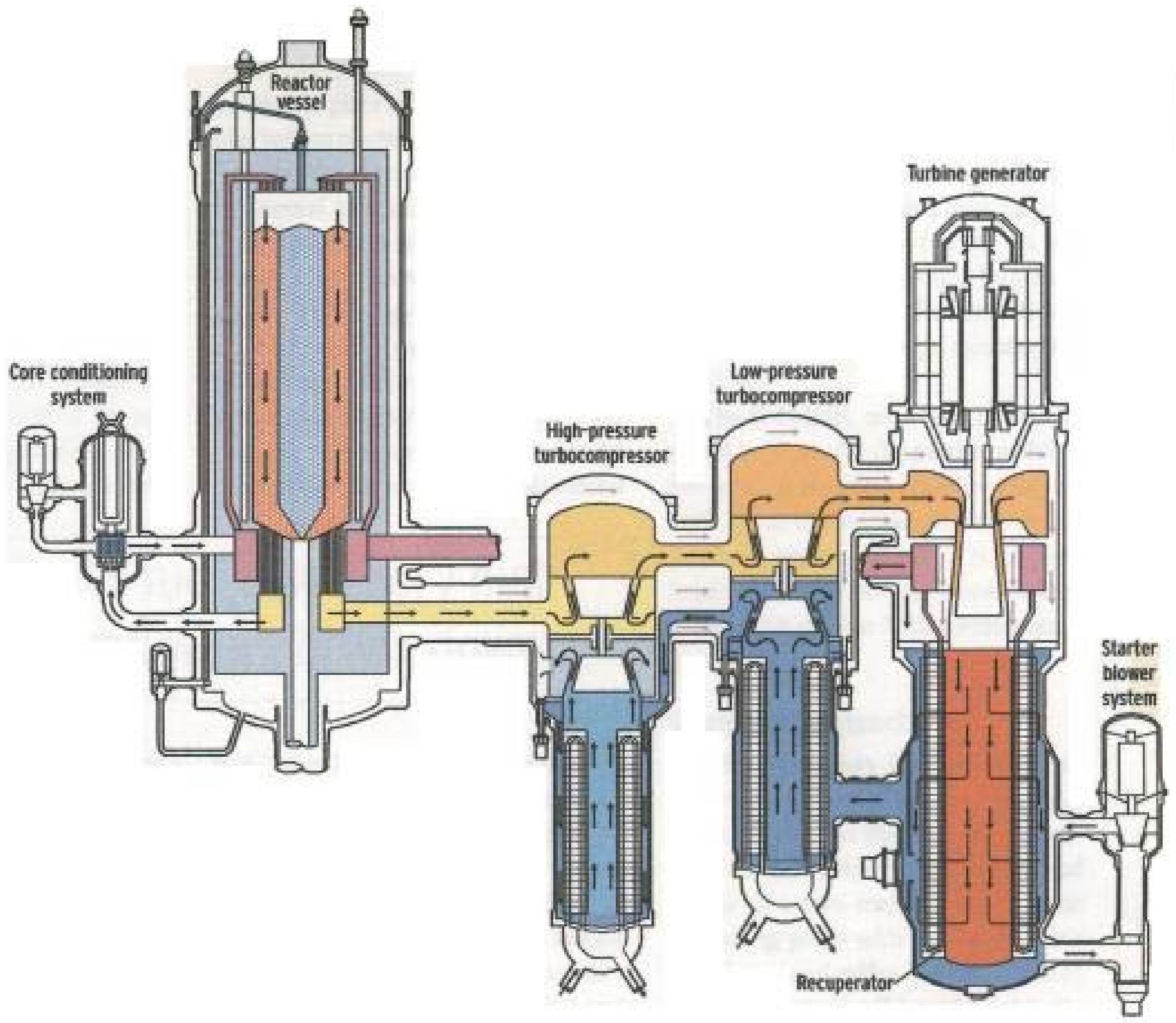
Molten Salt Reactor Fuel



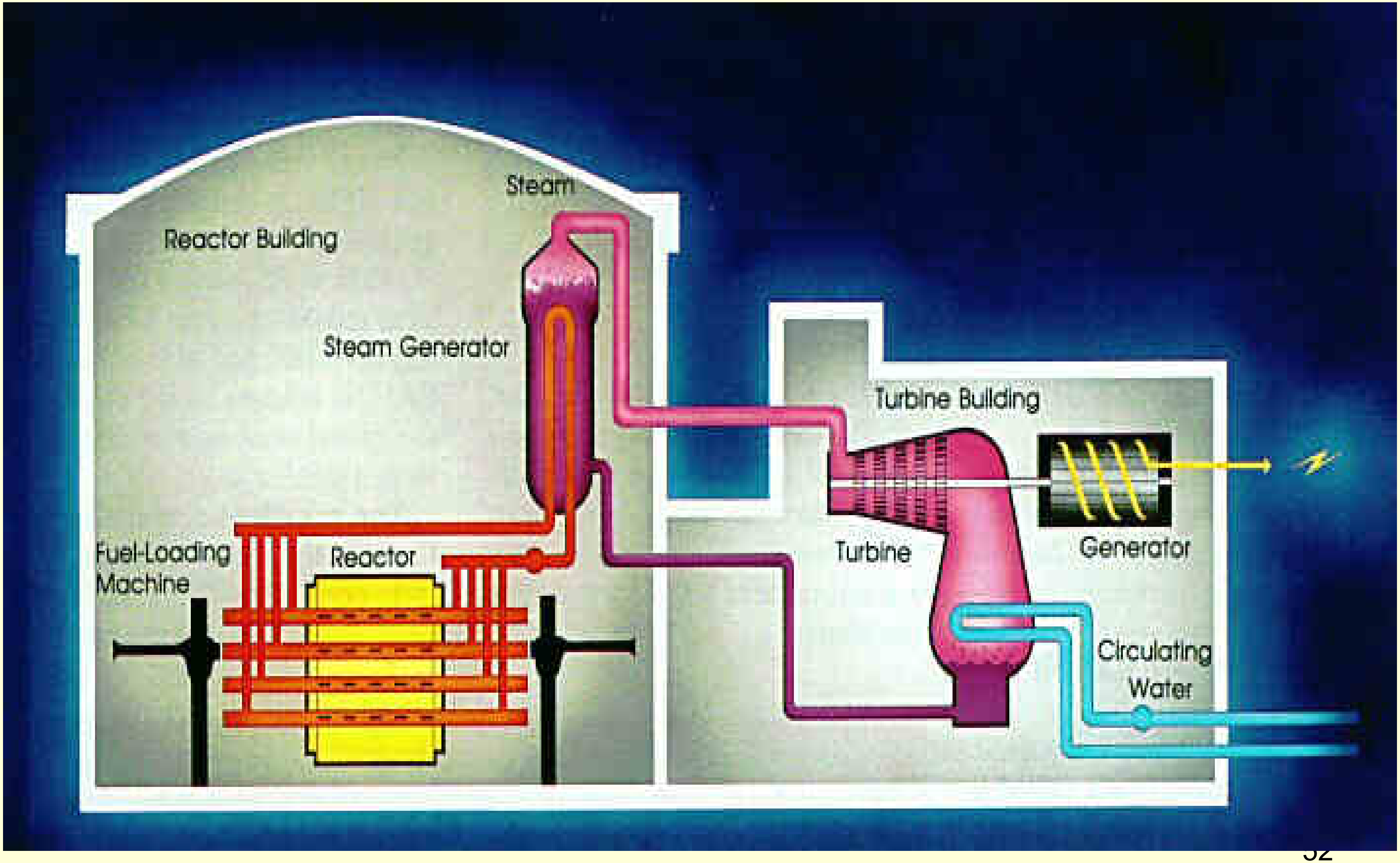
Supercritical-Water-Cooled Reactor



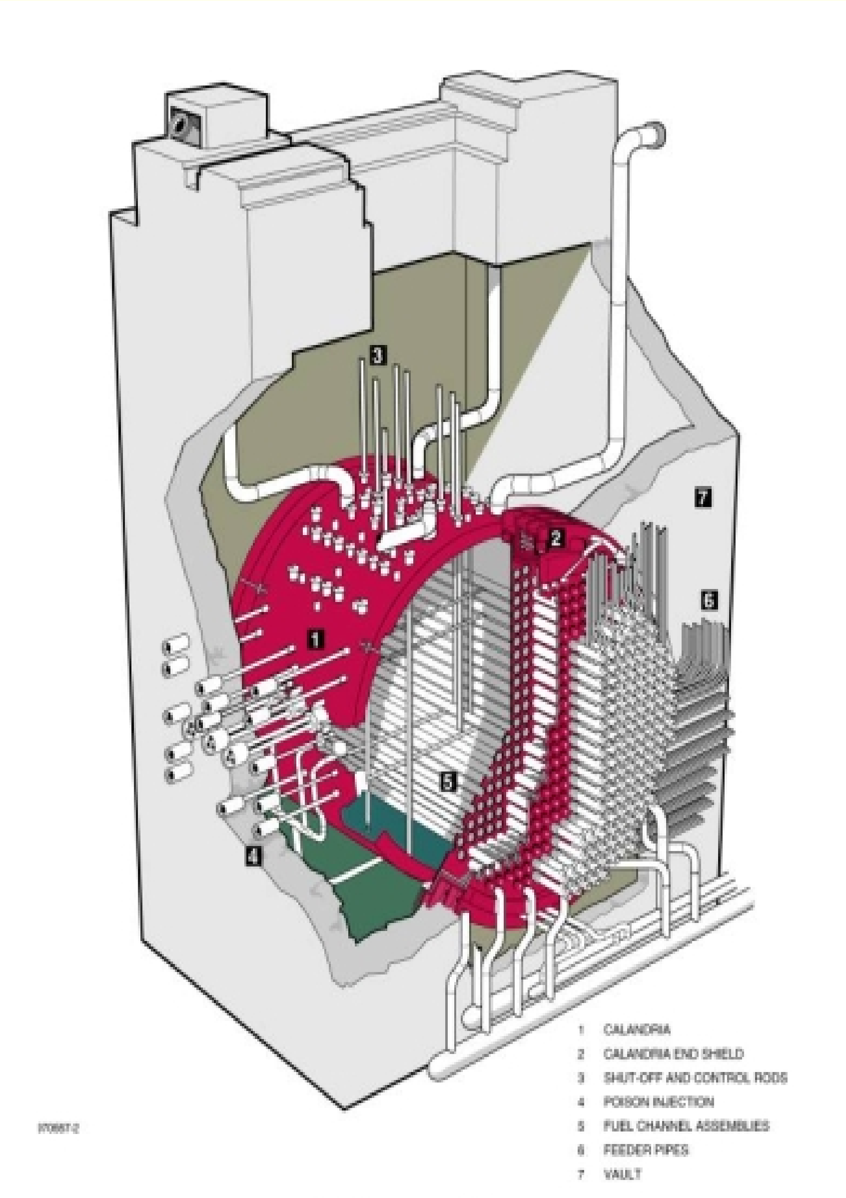
Pebble-Bed Modular Reactor



Canada Deuterium-Uranium Reactor



CANDU Calandria Schematic



CANDU 6 Reactor Assembly

CANDU Calandria Photo

CANDU Fuel Assembly

CANDU Online Refueling