# Chemical Engineering 412

*Introductory Nuclear Engineering*

Lecture 21

Nuclear Power Plants I

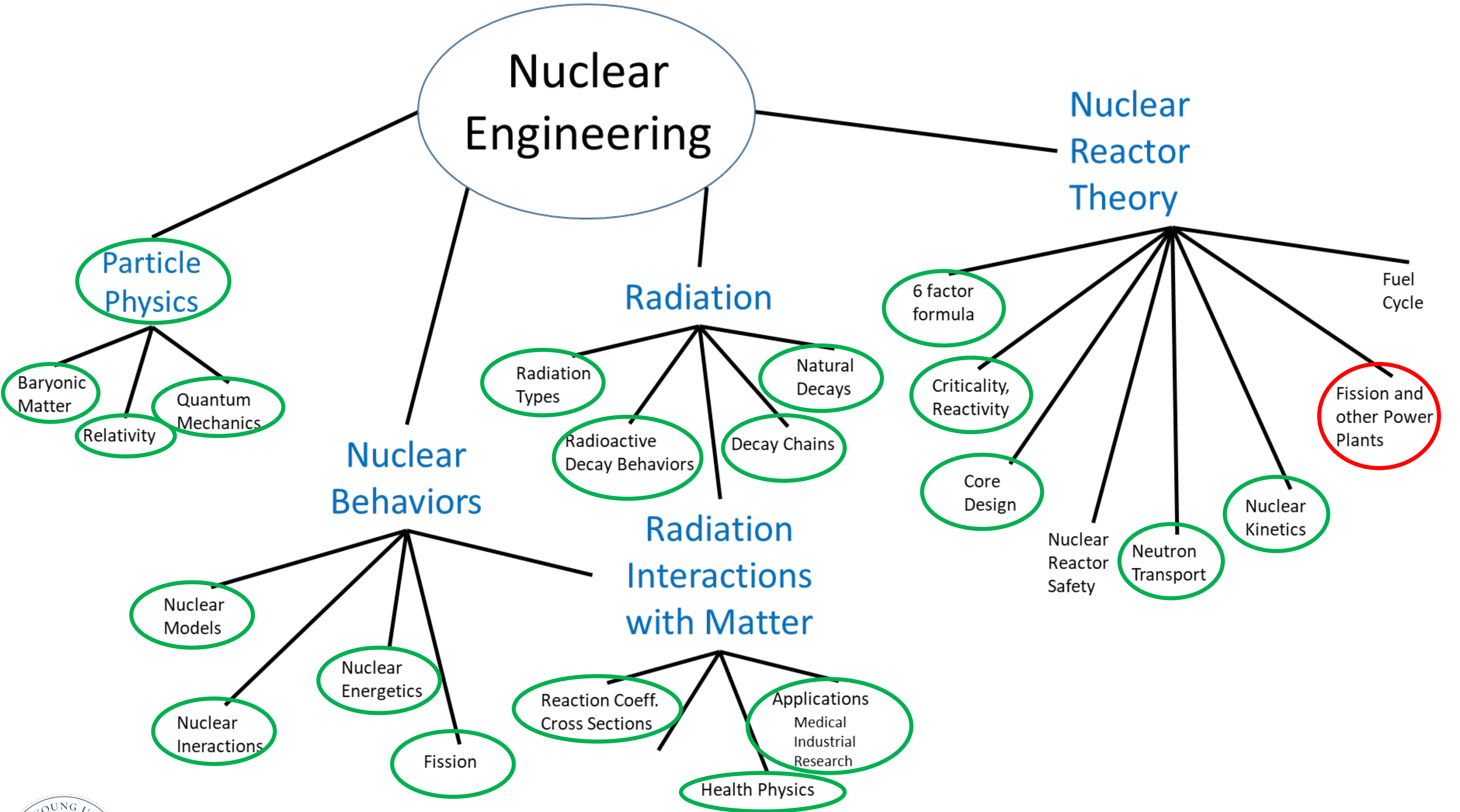
Nuclear Power Plant Types

# Spiritual Thought

"Today is Palm Sunday. We are preparing to commemorate the most important and transcendent event ever recorded on earth, which is the Atonement and Resurrection of the Lord Jesus Christ. One of the best ways we can honor the Savior is to become a peacemaker."

-Presdient Russel M. Nelson

# Roadmap



Nuclear Engineering
Particle Physics
Baryonic Matter
Relativity
Quantum Mechanics
Nuclear Behaviors
Nuclear Models
Nuclear Ineractions
Nuclear Energetics
Fission
Radiation
Radiation Types
Radioactive Decay Behaviors
Natural Decays
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

# Historical Nuclear Challenges

- Radiation


- Safety


- Nuclear Waste

- Weapons/ Proliferation

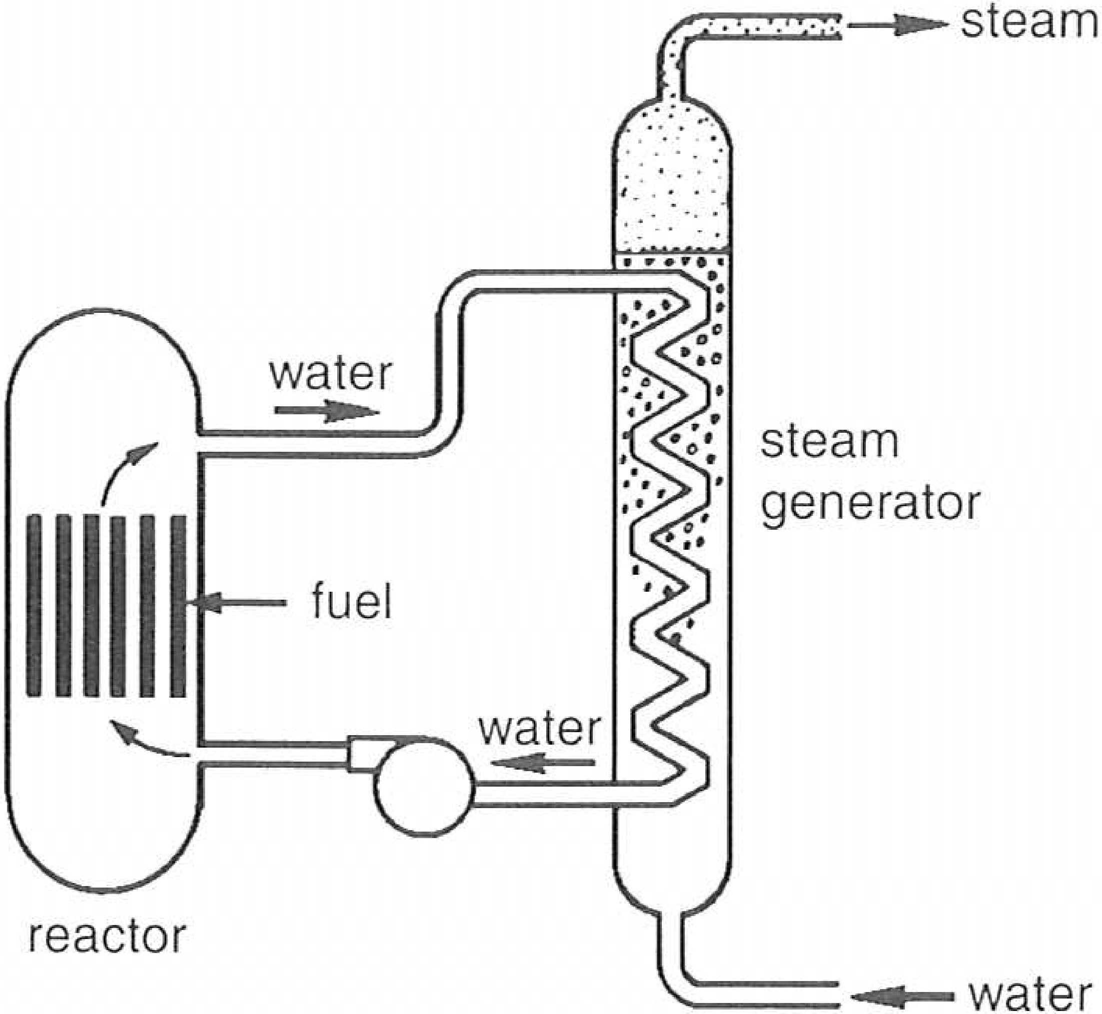
- Economics

# Reactor Startup



Sandia National Laboratories

# Pressurized Water Reactor (PWR)

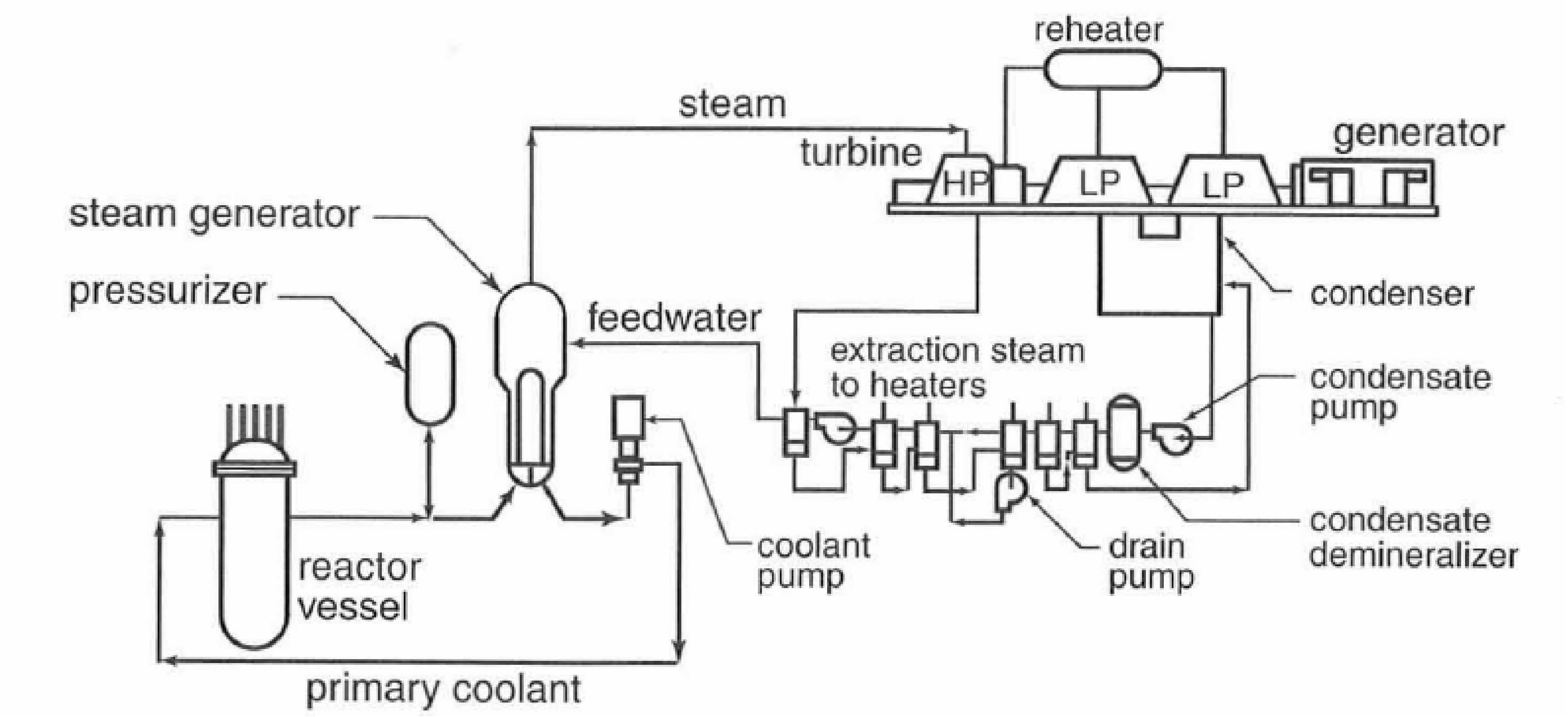


# Pressurized Water Reactor (PWR)

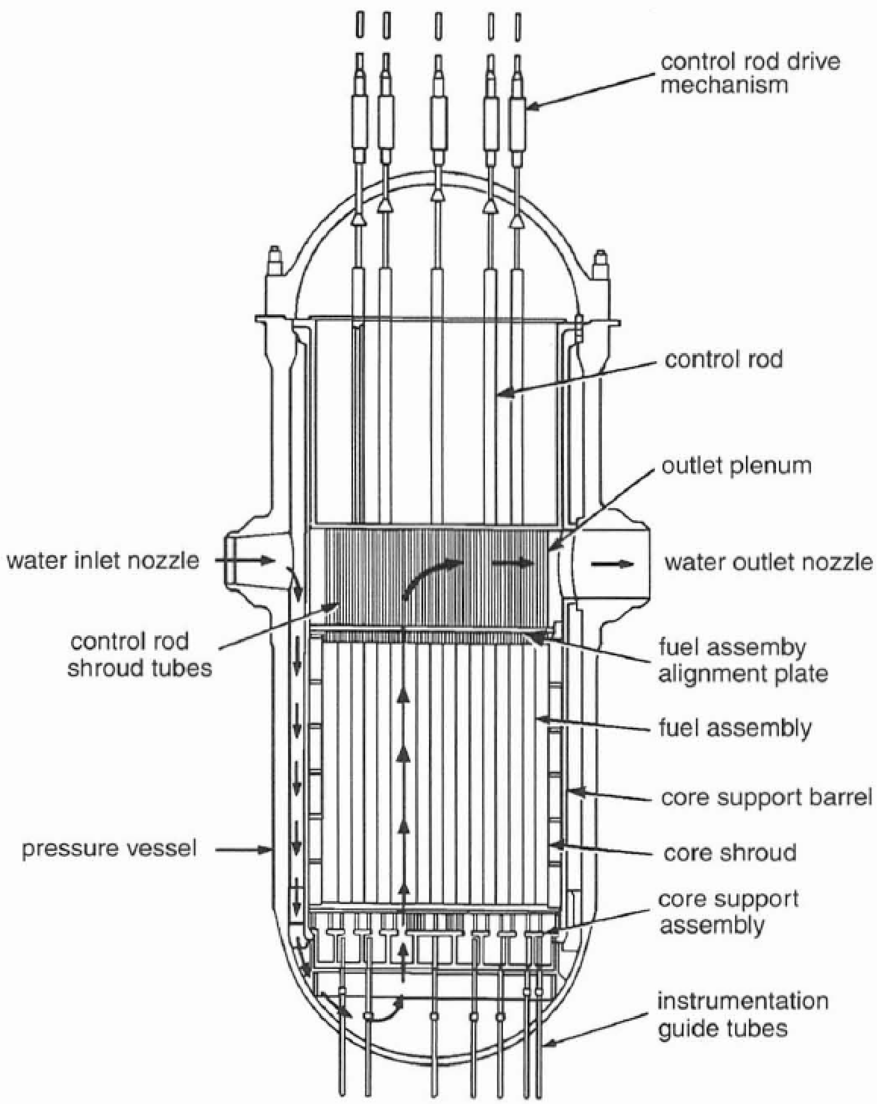
- Most widely used reactor worldwide.
- Water never boils in the core (which is pressurized – typically 150-200 atm).
- Heat exchanged in a second lower-pressure loop to generate turbine steam.
- Minimizes equipment exposure to ionizing radiation and radioactive waste production.

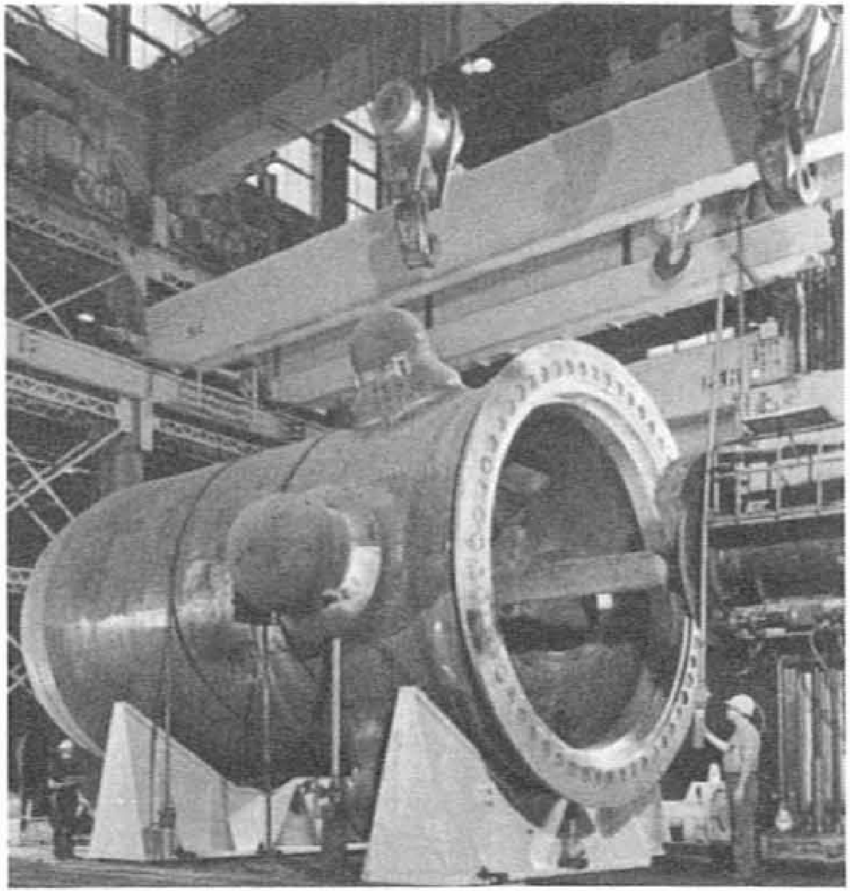
BRIGHAM YOUNG UNIVERSITY FOUNDED BYU 1875 PROVO, UTAH

# PWR Steam Cycle

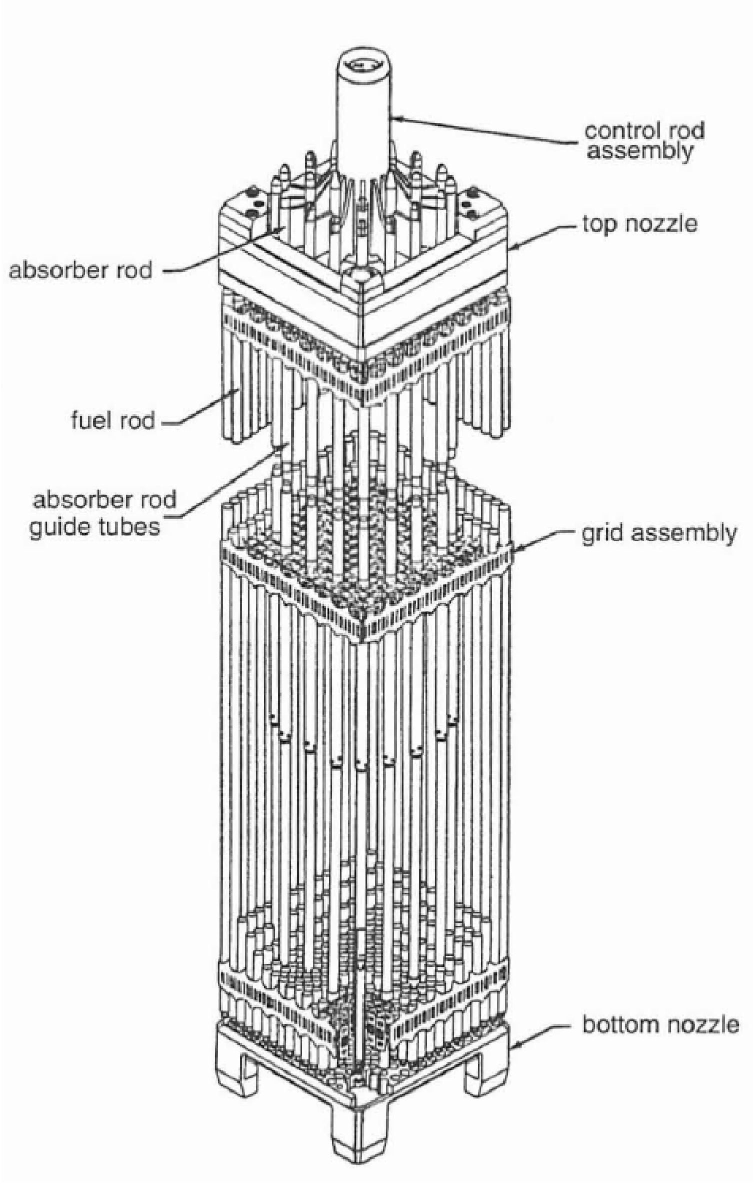


# Reactor Core

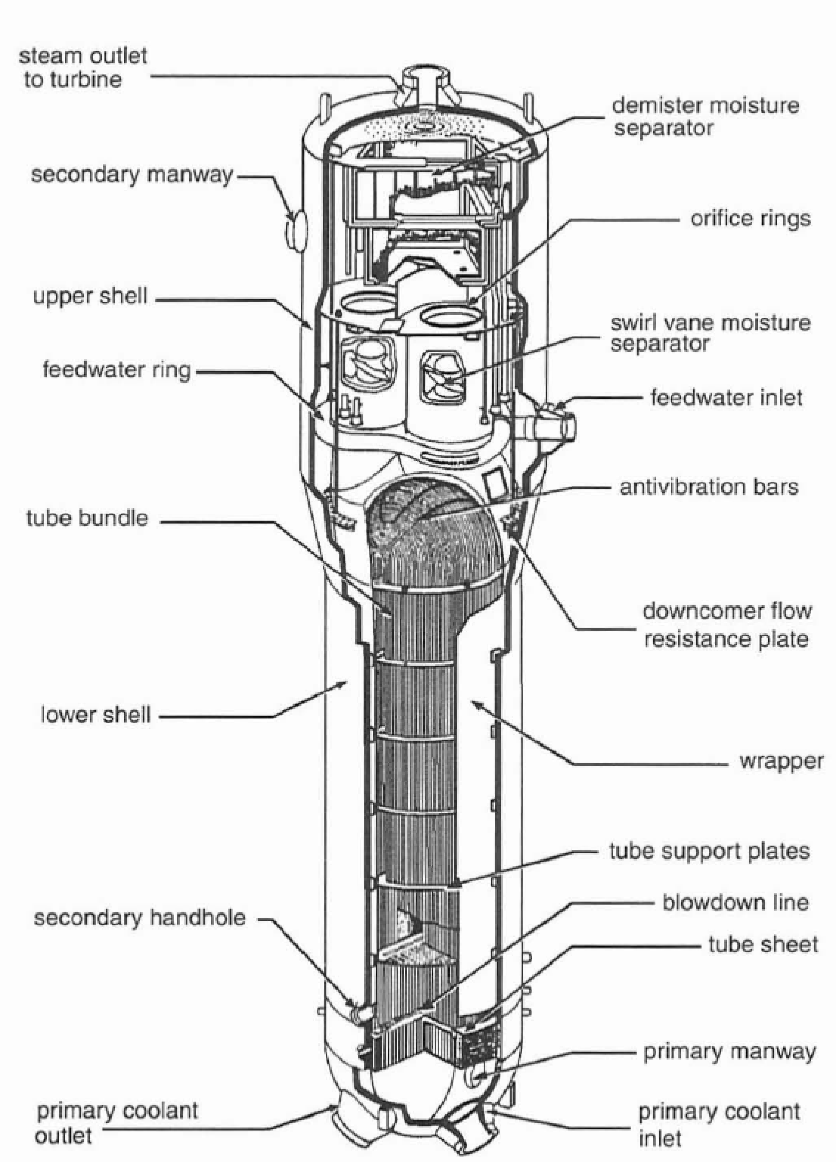


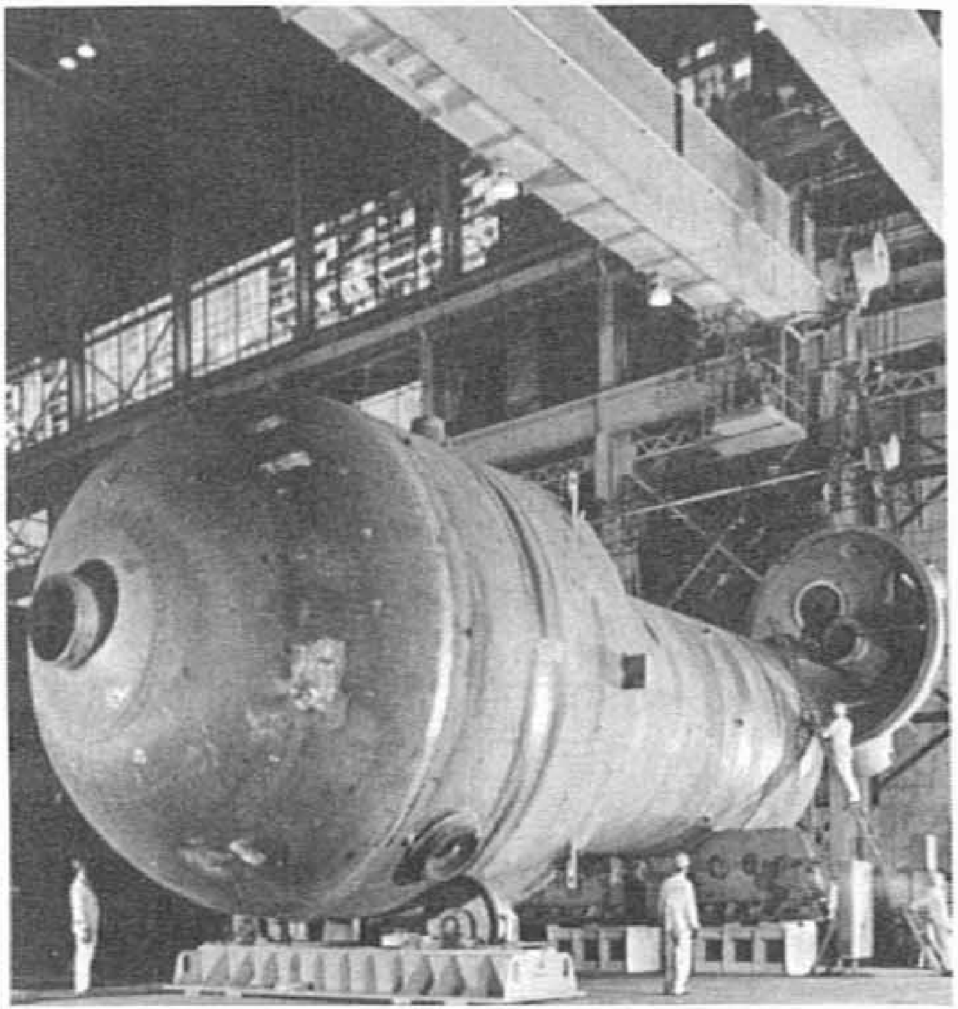



# Fuel Assembly

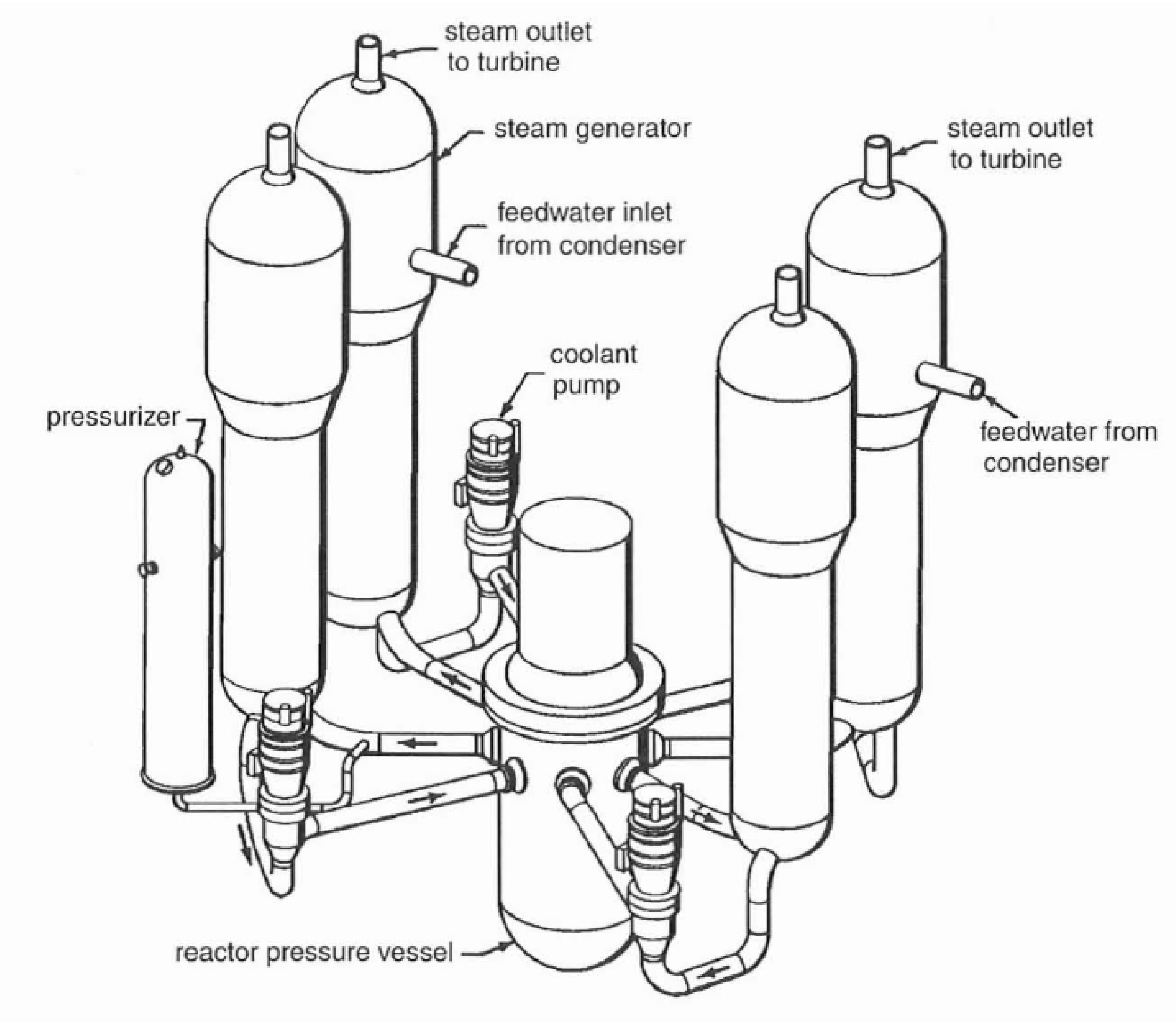


# Steam Generator (Heat Exchanger)

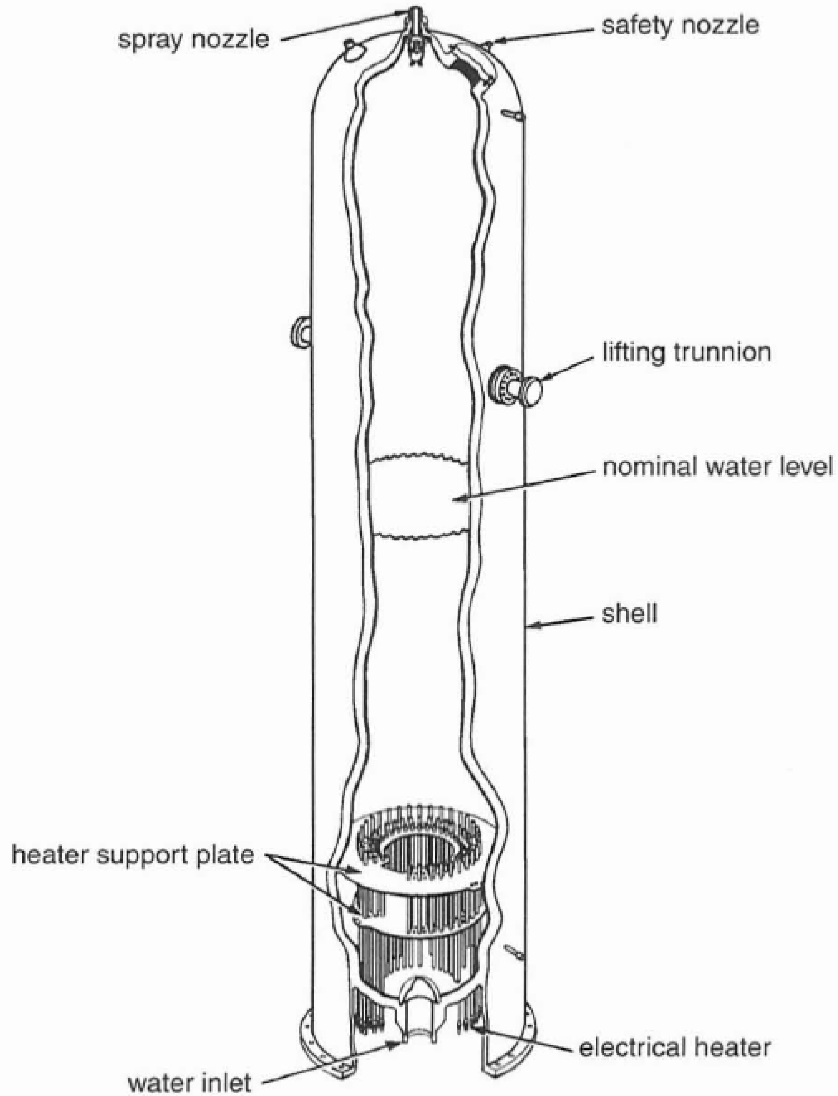


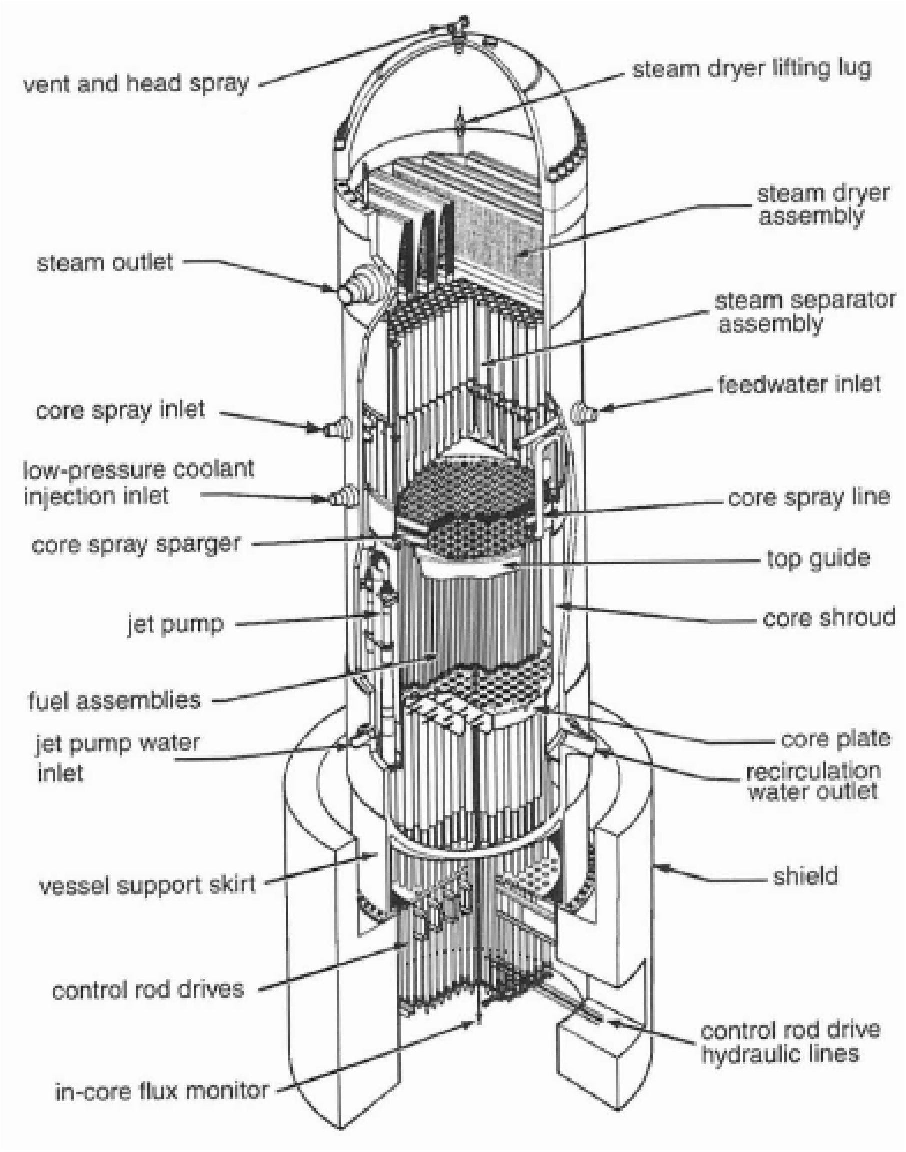
# Overall Equipment Arrangement



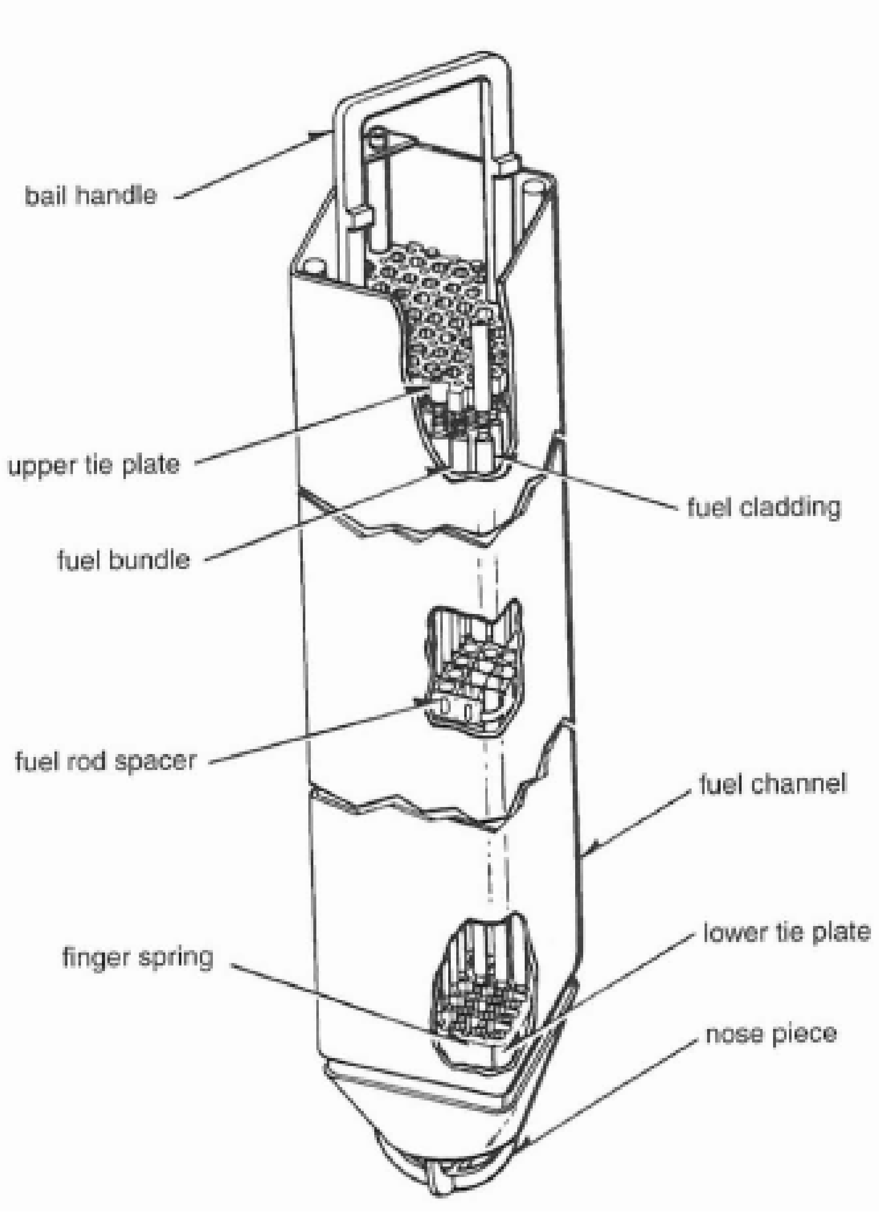
# Pressurizer



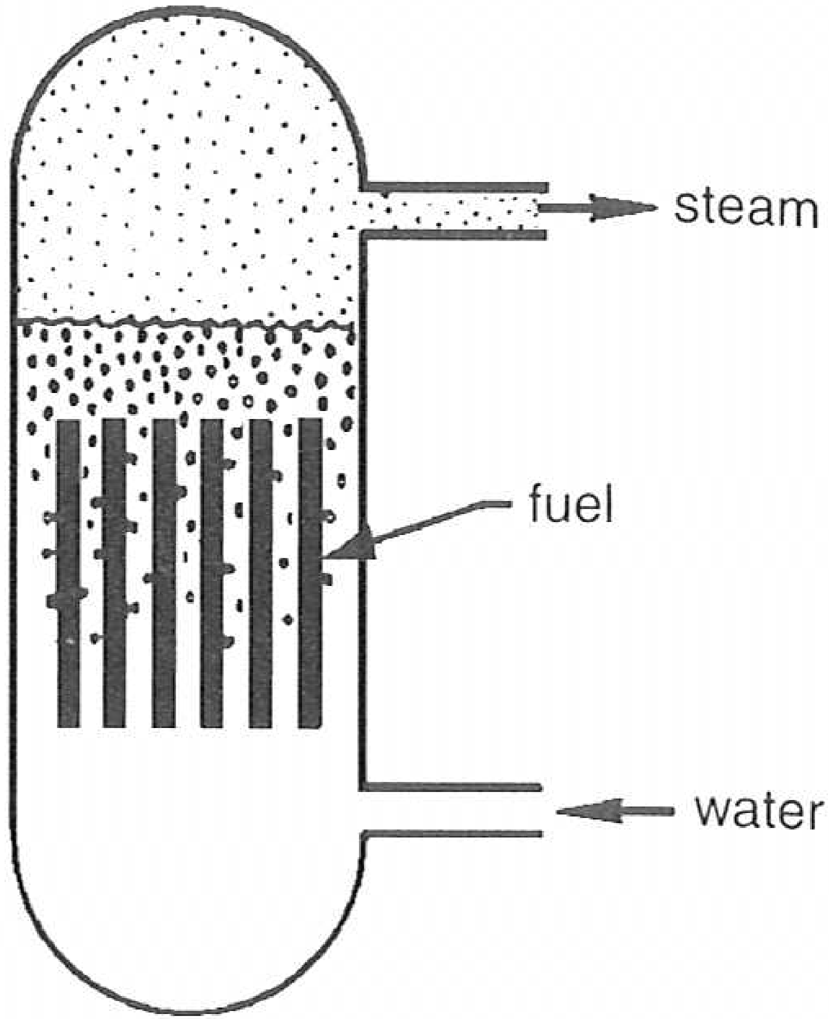
# BWR Core


vent and head spray
steam dryer lifting lug
steam dryer assembly
steam outlet
steam separator assembly
feedwater inlet
core spray inlet
low-pressure coolant injection inlet
core spray line
core spray sparger
top guide
jet pump
core shroud
fuel assemblies
core plate
jet pump water inlet
recirculation water outlet
vessel support skirt
shield
control rod drives
control rod drive hydraulic lines
in-core flux monitor

# BWR Fuel Assembly



# Boiling Water Reactor (BWR)



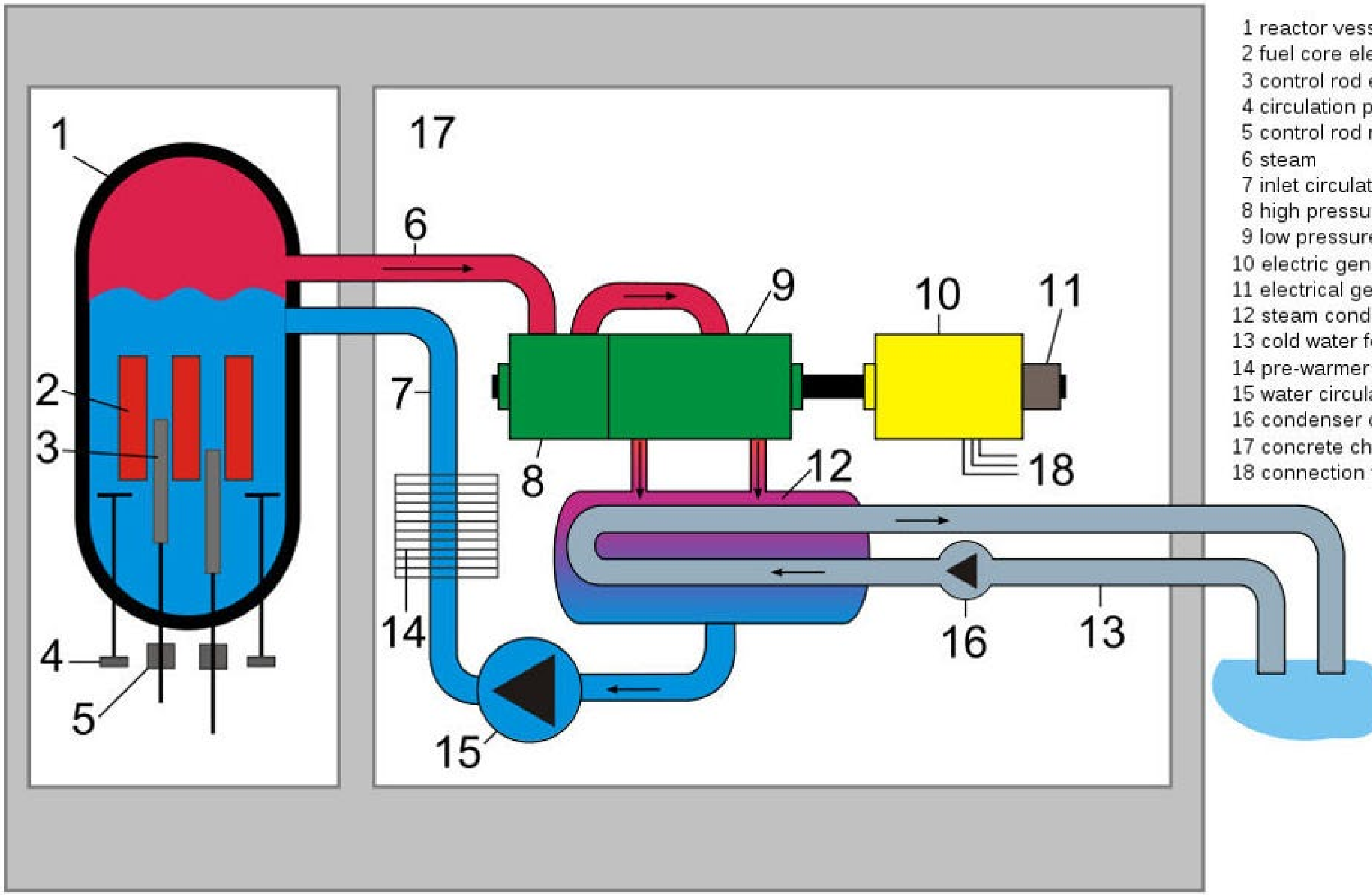
# Boiler Water Reactor (BWR)

- Water boils directly in the core.
- Steam passes directly to turbine.
- After turbine, steam recondenses and returns to reactor.
- Large variations in heat transfer coefficients on the fuel rods.
- Turbine exposed to radioactive products from fluid, complicating maintenance and decommissioning.

# BWR Specifications

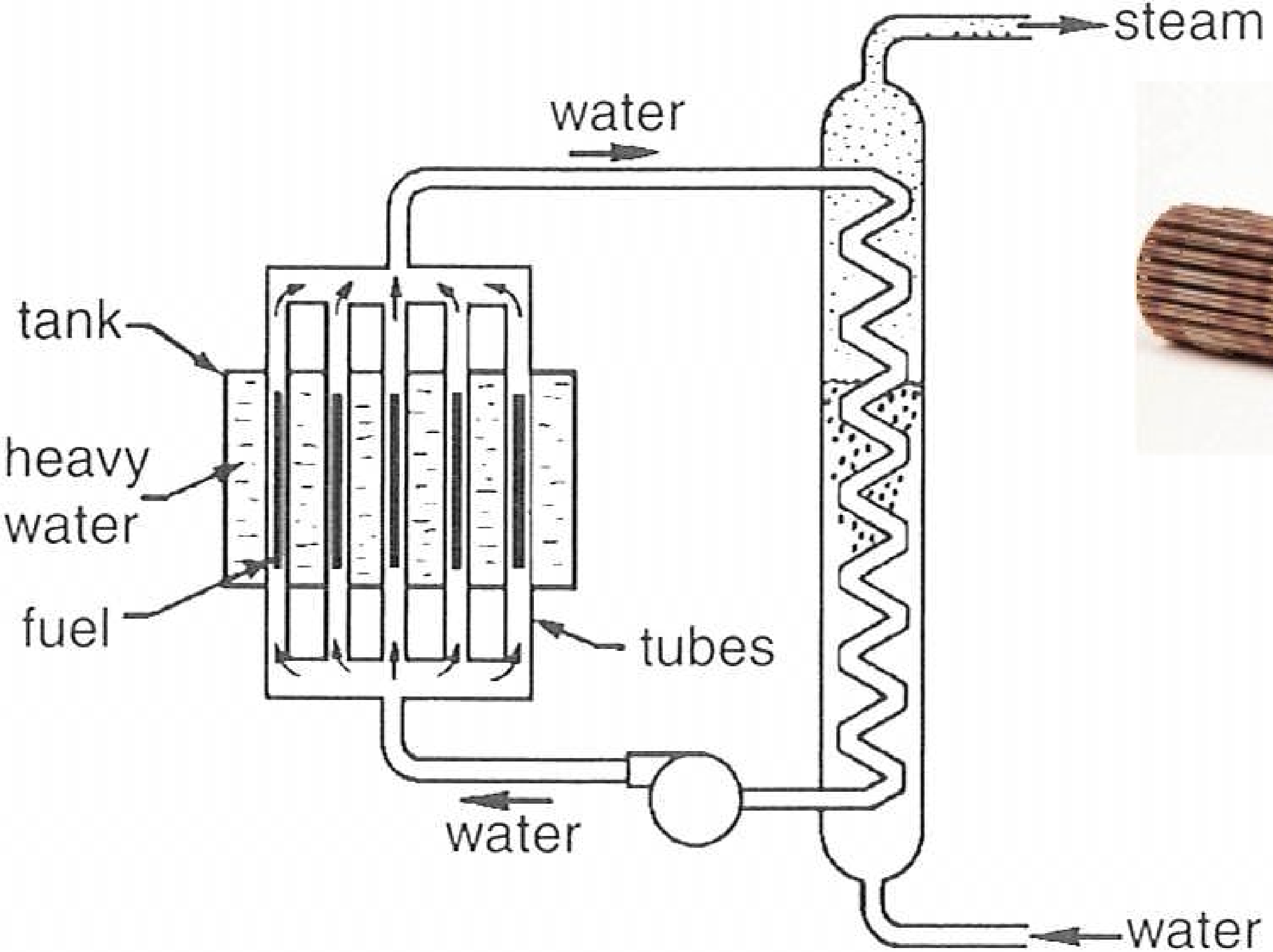
| | |
|---|---|
| **POWER** | |
| thermal output | 3830 MW |
| electrical output | 1330 MW(e) |
| efficiency | 0.34 |
| **CORE** | |
| length | 3.76 m |
| diameter | 4.8 m |
| specific power | 25.9 kW/kg(U) |
| power density | 56 kW/L |
| av. linear heat rate | 20.7 kW/m |
| rod surface heat flux | |
| average | 0.51 $MW/m^2$ |
| maximum | 1.12 $MW/m^2$ |
| **REACTOR COOLANT SYSTEM** | |
| operating pressure | 7.17 MPa (1040 psia) |
| feedwater temperature | 216 °C |
| outlet steam temperature | 290 °C |
| outlet steam flow rate | $7.5 \times 10^6$ kg/h |
| core flow rate | $51 \times 10^6$ kg/h |
| core void fraction (av.) | 0.37 |
| core void fraction (max.) | 0.75 |
| no. in-core jet pumps | 24 |
| no. coolant pumps/loops | 2 |

| | |
|---|---|
| **REACTOR PRESSURE VESSEL** | |
| inside diameter | 6.4 m |
| total height | 22.1 m |
| wall thickness | 15 cm |
| **FUEL** | |
| cylindrical fuel pellets | $UO_2$ |
| pellet diameter | 10.57 mm |
| rod outer diameter | 12.52 mm |
| zircaloy clad thickness | 0.864 mm |
| rod lattice pitch | 16.3 mm |
| rods/assembly (8 × 8) | 62 |
| assembly width | 13.4 cm |
| assembly height | 4.48 m |
| fuel assemblies in core | 760 |
| fuel loading | $168 \times 10^3$ kg |
| av. initial enrichment % $^{235}U$ | 2.6% |
| equil. enrichment % $^{235}U$ | 1.9% |
| discharge fuel burnup | 27.5 GWd/tU |
| **REACTIVITY CONTROL** | |
| no. control elements | 193 |
| shape | cruciform |
| overall length | 4.42 m |
| length of poison section | 3.66 m |
| neutron absorber | boron carbide |
| burnable poison in fuel | gadolinium |




1 reactor vessel
2 fuel core element
3 control rod element
4 circulation pumps
5 control rod motors
6 steam
7 inlet circulation water
8 high pressure turbine
9 low pressure turbine
10 electric generator
11 electrical generator exciter
12 steam condenser
13 cold water for condenser
14 pre-warmer
15 water circulation pump
16 condenser cold water pum
17 concrete chamber
18 connection to electricity gr

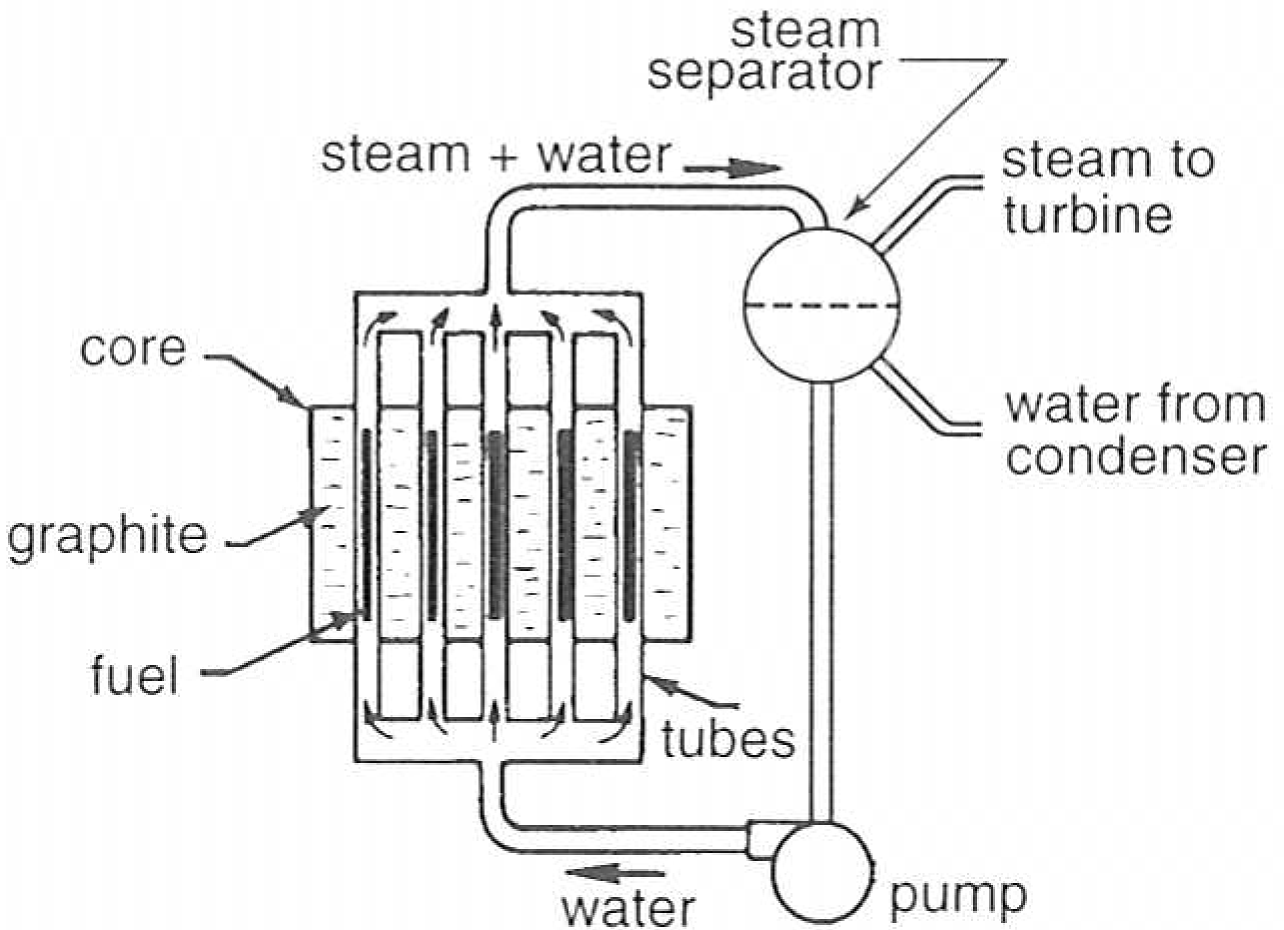
# Heavy Water Reactor (PHWR)




# Heavy Water Reactor

- Heavy water (deuterium- or tritium-based water) passes through pressurized fuel tubes surrounded by a non-pressurized heavy water bath.
- Operates on natural uranium
- Avoids pressurized reactor vessel (major expense).
- Steam generated in second loop.
- Basis of the CANDU (Canadian) reactor designs.
- Variant is the heavy-water-moderated, light-water-cooled reactor (HWLWR) that uses light water in the fuel tubes and no heat exchanger.

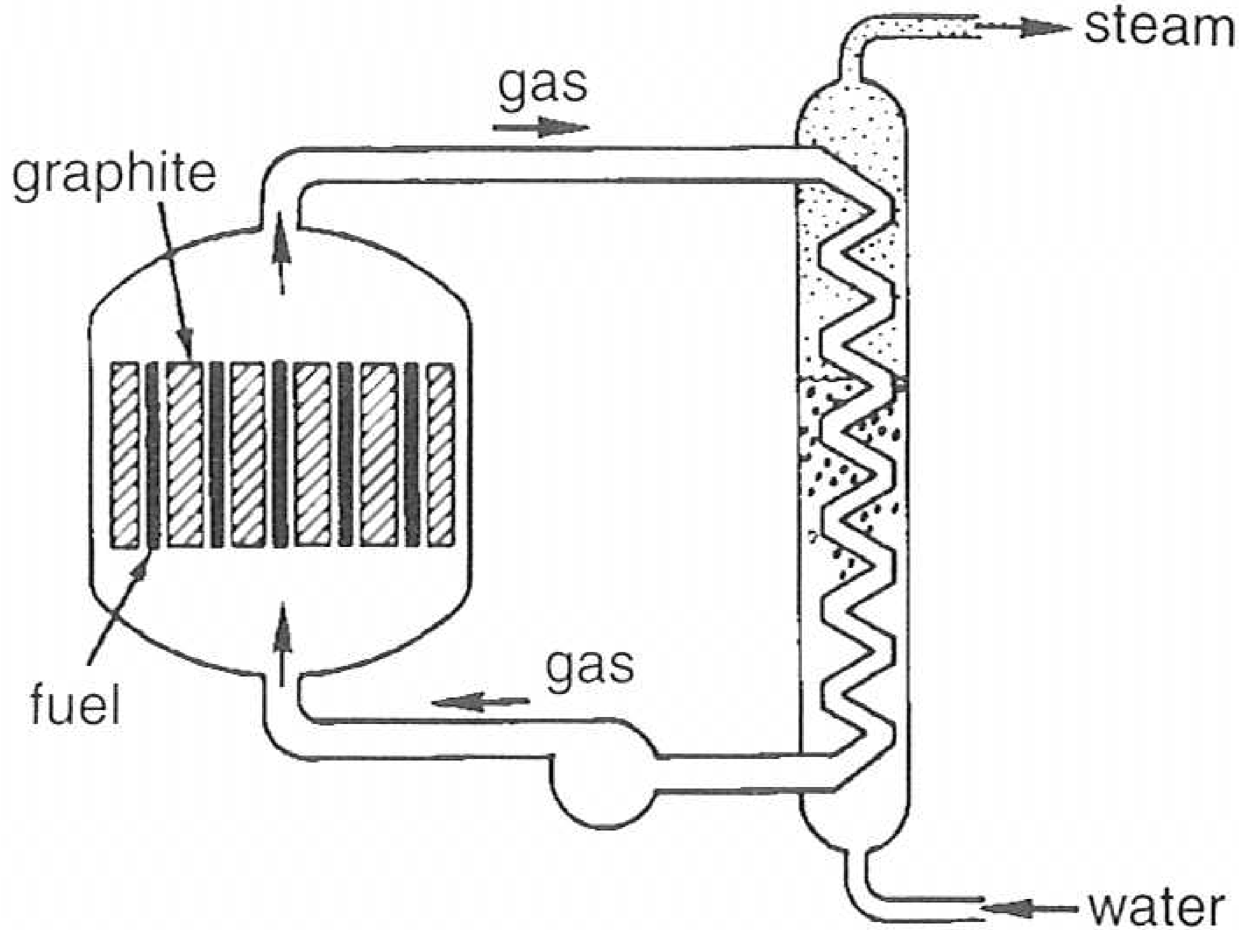
# Light-water-cooled graphite moderated reactor (LGR)



# Light-water-cooled graphite moderated reactor (LGR)

- Soviet-designed reactor, called RBMK (reactory bolshoi moshchnosti kanalnye – high-powered pressure-tube reactor).
- Fuel in fuel pressurized fuel channels in graphite block.
- Steam passes directly to turbine.
- Fuel can be exchanged without reactor shutdown.
- Capable of operation on natural uranium.
- All systems since Chernobyl use higher (2.4%) uranium enrichment.

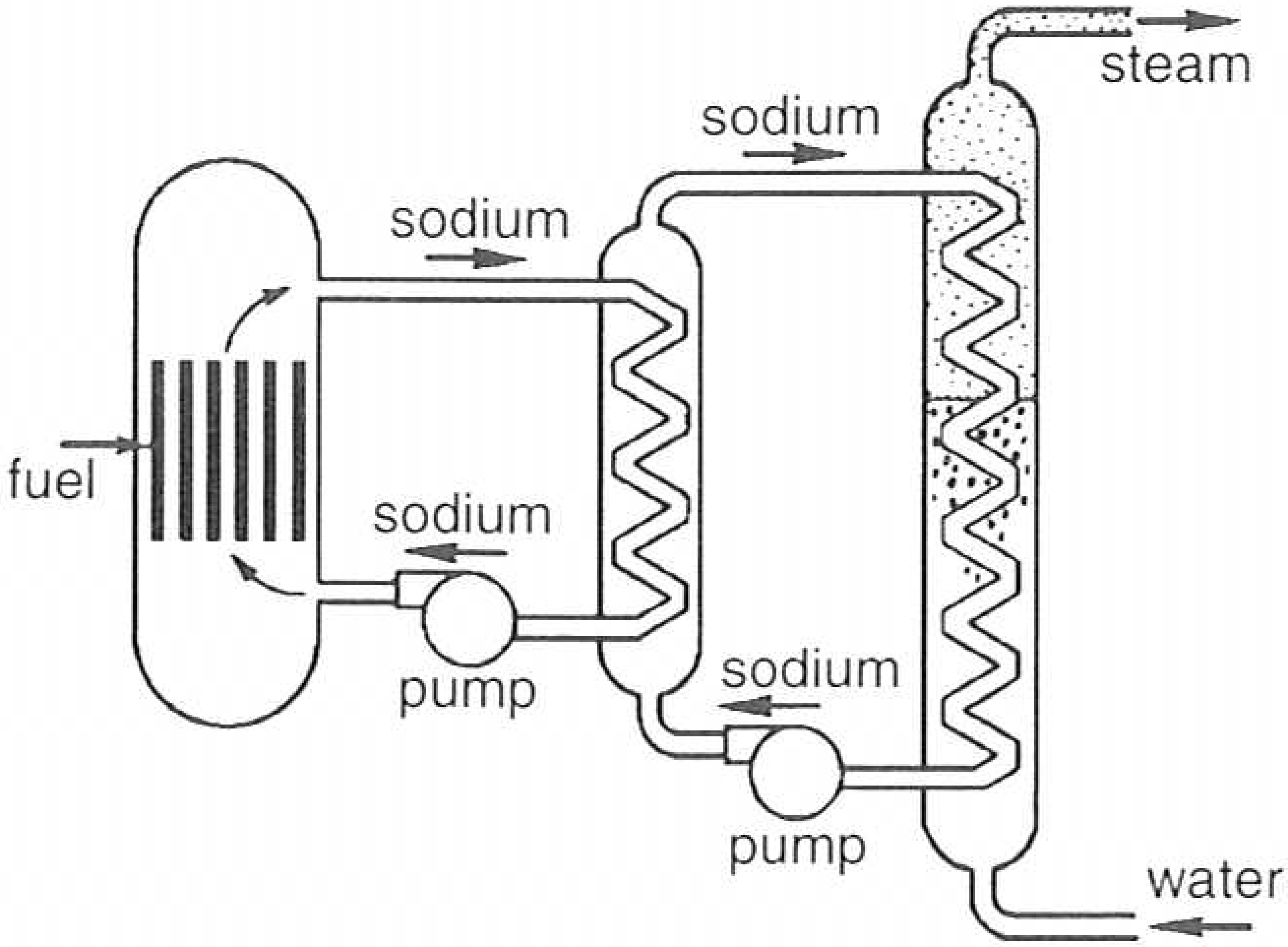
# Gas-cooled Reactor (GCR)



# Gas-cooled Reactor (GCR, HTGR)

- Gas (He or $CO_2$) used as coolant.
- Graphite typically used as moderator.
- Graphite (which remains solid) and gas need not be pressurized
  - No expensive pressure vessel
  - No Blowdown in accident
- Gas heats steam in secondary loop.
- In a gas-cooled reactor (GCR), gas passes through holes in graphite moderator.
- In a high-temperature gas-cooled reactor (HTGR), fuel channels and gas channels are drilled in graphite core.

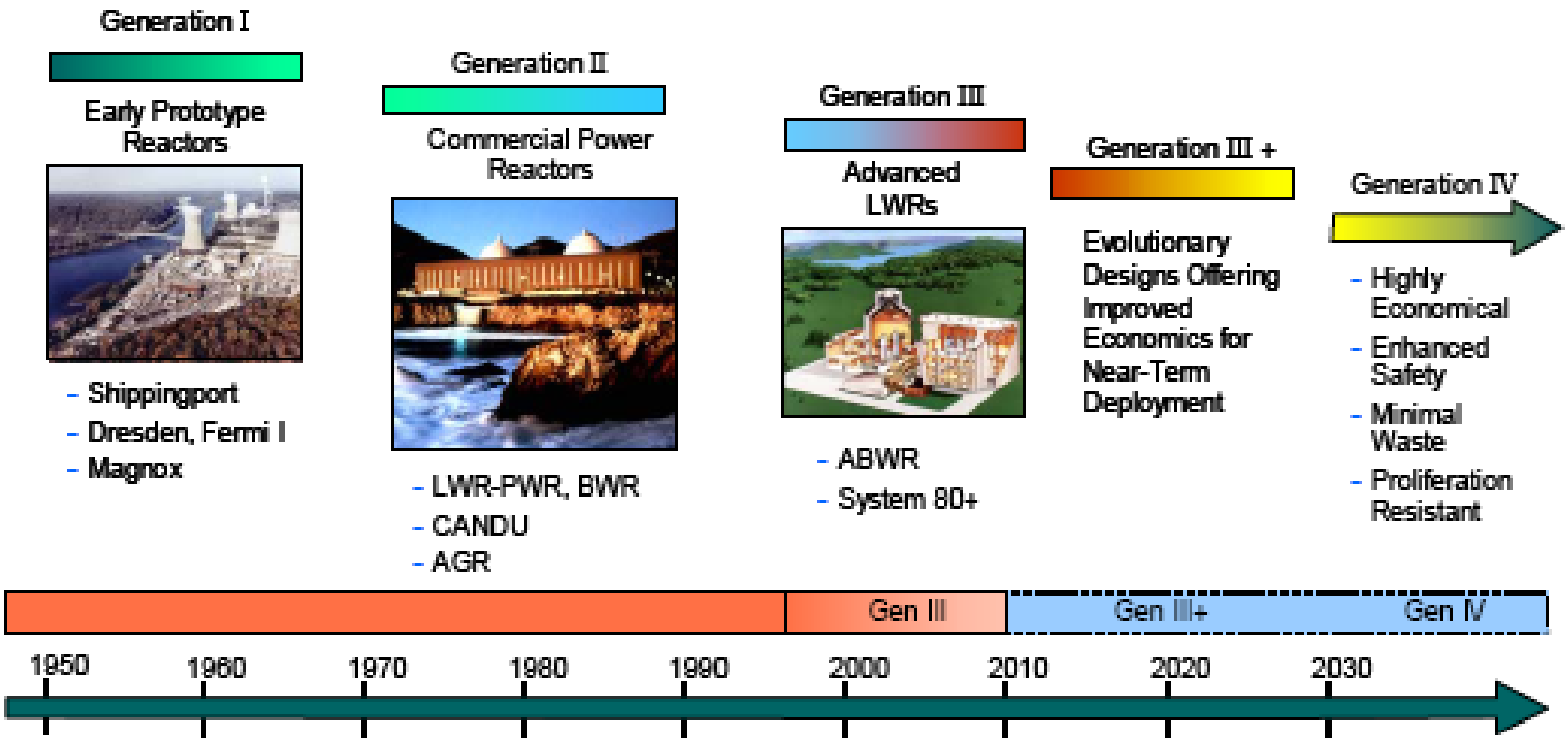
# Liquid-metal fast breeder reactor



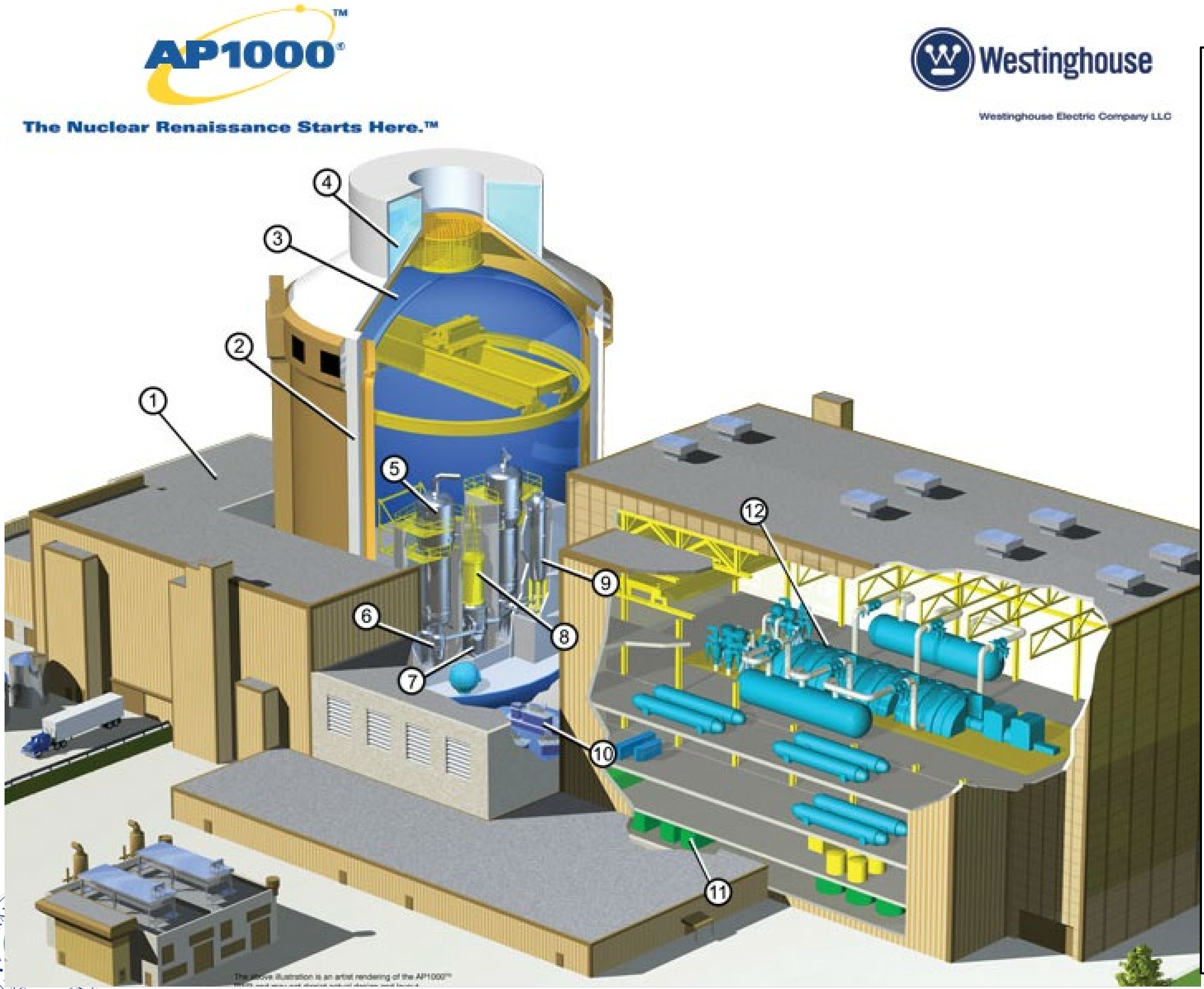
# Liquid Metal Fast Breeder Reactor (LMFBR)

- Fast-neutron-based reactor scheme.
- No moderator (no light elements).
- Na or K-Na molten metal used as coolant.
- No pressurization, very high heat transfer coefficients.
- Na becomes radioactive and Na and K react violently with water (moderately with air).
- Second Na heat exchanger isolates Na/K coolant in core from turbine steam.
- New fuel to consumed fuel ratio raises from 0.6-0.8 in typical reactors to over 1 if designed as a breeder reactor.
- One in commercial operation (in Russia), though they are aggressively pursuing new designs.

# Generations I-IV



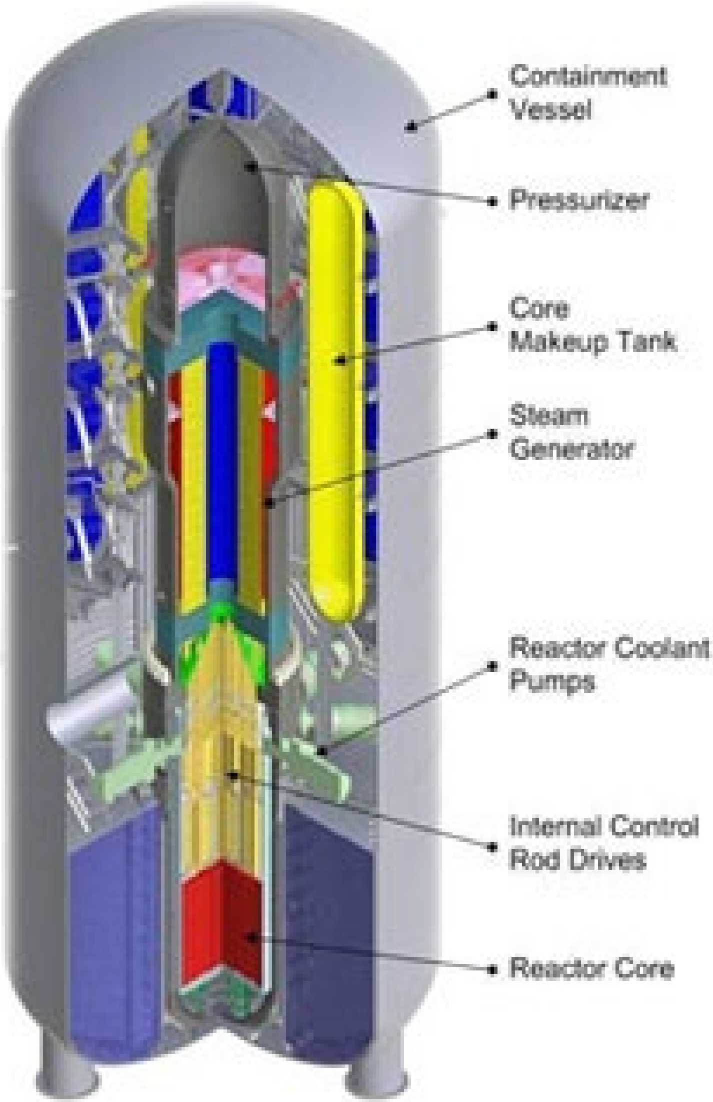
# The AP1000 (Gen III+) Design

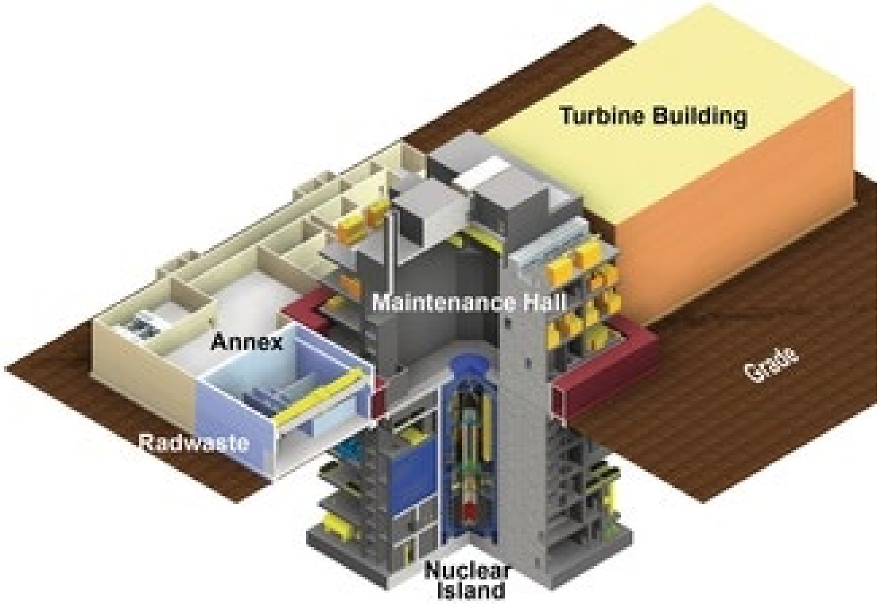


# Small Modular Reactors

- Small is $< 300$ $MW_e$ (IAEA definition) or $< 500$ $MW_e$ (conventional definition).
- Modular means systems can be almost entirely fabricated in shops rather than on site, decreasing security and other risks.
- Primary advantage is decrease in capital cost, reducing financial risk, construction at a single location, ability to add incremental power.
- Primary disadvantage is loss of economies of scale. Four small reactors are more expensive to build and operate than one large reactor of equivalent size.
- Include III, III+, and IV or other designs

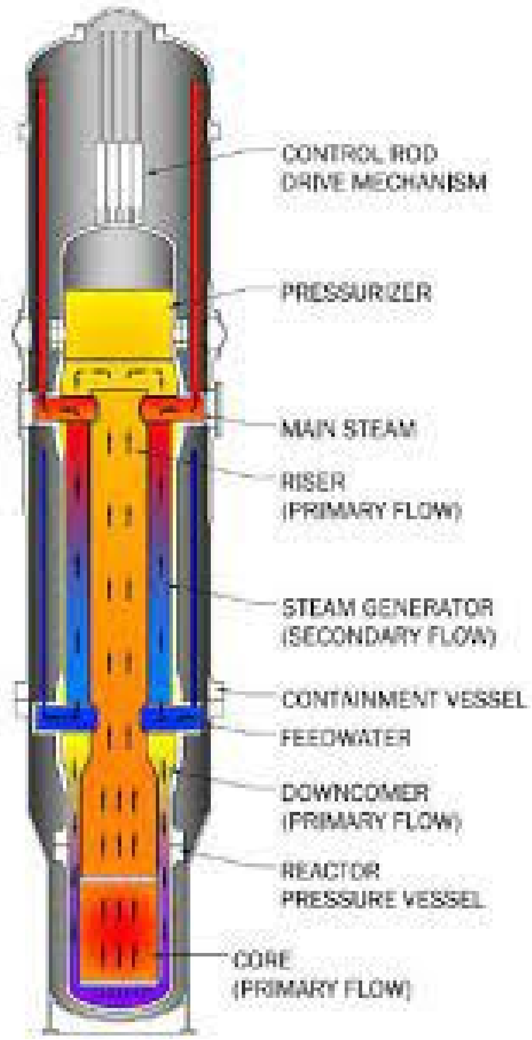
# Westinghouse SMR



# NuScale Reactor

- Voyager SMR Plants
- 77 MWe per module
- 4, 8, 12 module packs
- 76’ x 15’ cylinder
- ~700 tons, 3 segment shipping
- 17x17 fuel assemblies
- 24 month fuel cycle
- Natural circulation only
- 10-13¢/kW-hr (initially 3.8 ¢/kW-hr)



# Small Modular Reactors

| Name | Power | Technology | Producer |
|---|---|---|---|
| VK-300 | 300 MWe | BWR | Atomstroyexport, Russia |
| S-PRISM | 311 MWe | FBR | GE Hitachi Nuclear Energy |
| 4S | 10–50 MWe | FNR | Toshiba - Japan |
| GT-MHR | 285 MWe | HTGR | General Atomics (USA), Minatom (Russia) et al. |
| PBMR | 165 MWe | HTGR | Eskom, South Africa, et al. |
| BREST[2] | 300 MWe | LFR | RDIPE (Russia) |
| Hyperion Power Module[1] | 25 MWe | LFR | Hyperion Pwr Gen - Santa Fe, NM USA |
| SVBR[3] | 10–100 MWe | LFR | OKB Gidropress (Russia) |
| MASLWR | 45 MWe | LWR | NuScale Power LLC, USA |
| Fuji MSR | 100–200 MWe | MSR | ITHMSO, Japan-Russia-USA |
| WAMSR | 200 MW | MSR | Transatomic Power, USA |
| CAREM | 27 MWe | PWR | CNEA & INVAP, Argentina |
| Flexblue | 50–250 MWe | PWR | Areva TA / DCNS group, France |
| IRIS-100 | 100 MWe | PWR | Westinghouse-led, international |
| KLT-40 | 35 MWe | PWR | OKBM, Russia |
| mPower | 180 MWE | PWR | Babcock & Wilcox, USA |
| MRX | 30–100 MWe | PWR | JAERI, Japan |
| NP-300 | 100–300 MWe | PWR | Areva TA, France |
| SMART | 100 MWe | PWR | KAERI, S. Korea |
| SMR-160 | 140 MWE | PWR | Holtec International, USA |
| Westinghouse SMR | 225 MWe | PWR | Westinghouse Electric Company, USA |
| TerraPower (Test Reactor) | 10 MWe | TWR | Intellectual Ventures - Bellevue, WA USA |

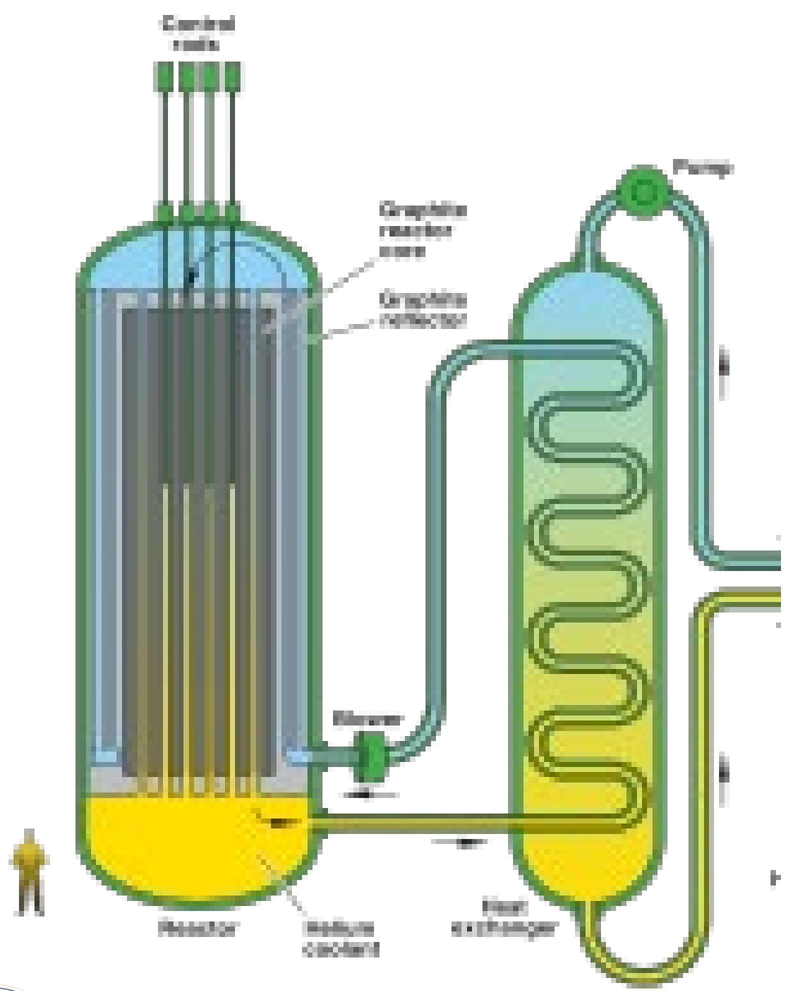
BWR - boiling water reactor
FBR - fast breeder reactor
FNR - fast neutron reactor
HTGR - high-temperature gas reactor

LFR - lead-cooled fast reactor
MSR - molten salt reactor
PWR - pressurized water reactor
TWR - traveling wave reactor

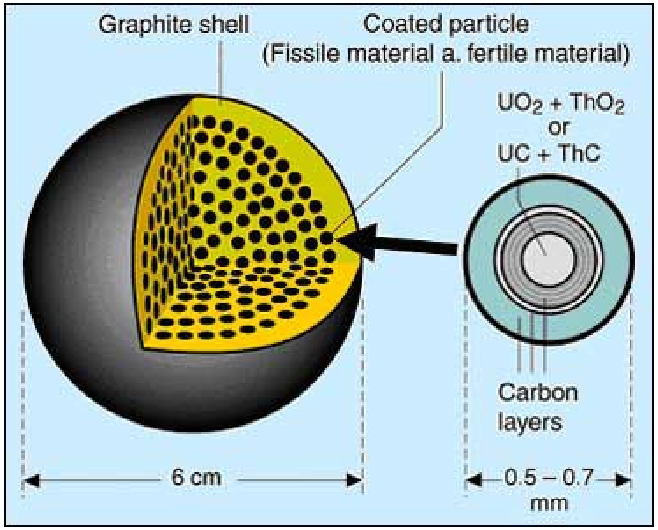
# Generation IV

- Advanced reactors
  - Address and solve key issues of Gen III
    - Safety, Cost, Waste, Weapons
- 6 primary types:
  - Gas Cooled Fast Reactors
  - Supercritical Water Reactors
  - Sodium Fast Reactors
  - Lead Fast Reactors
  - High Temperature Gas Reactors (Pebble Bed)
  - Molten Salt Reactors

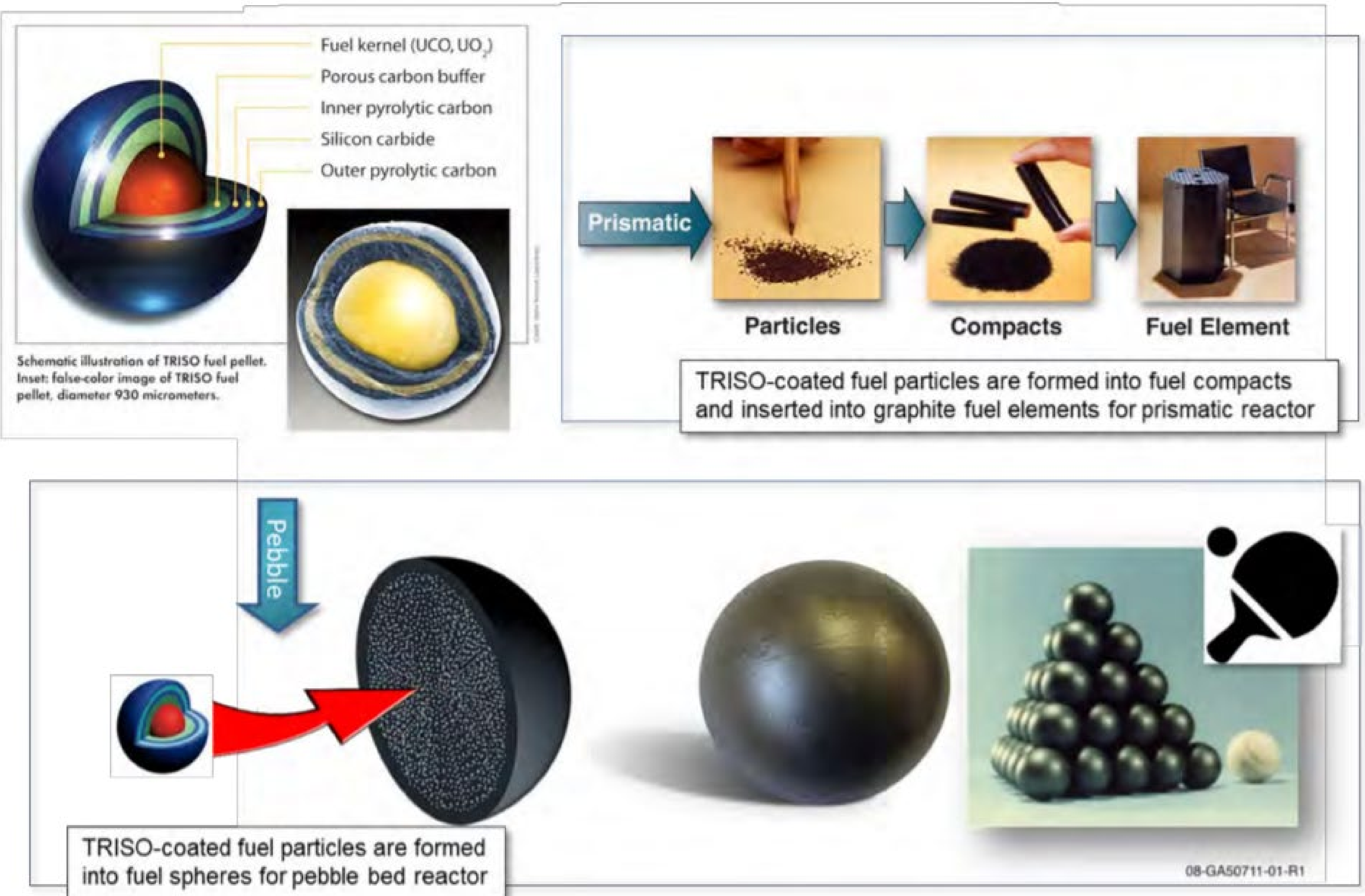
# Very High Temperature Reactor



- $T_{out}$ = 1000° C
- Gas cooled (He)
- Inherently safe
- Low Power Density
- Brayton Cycle

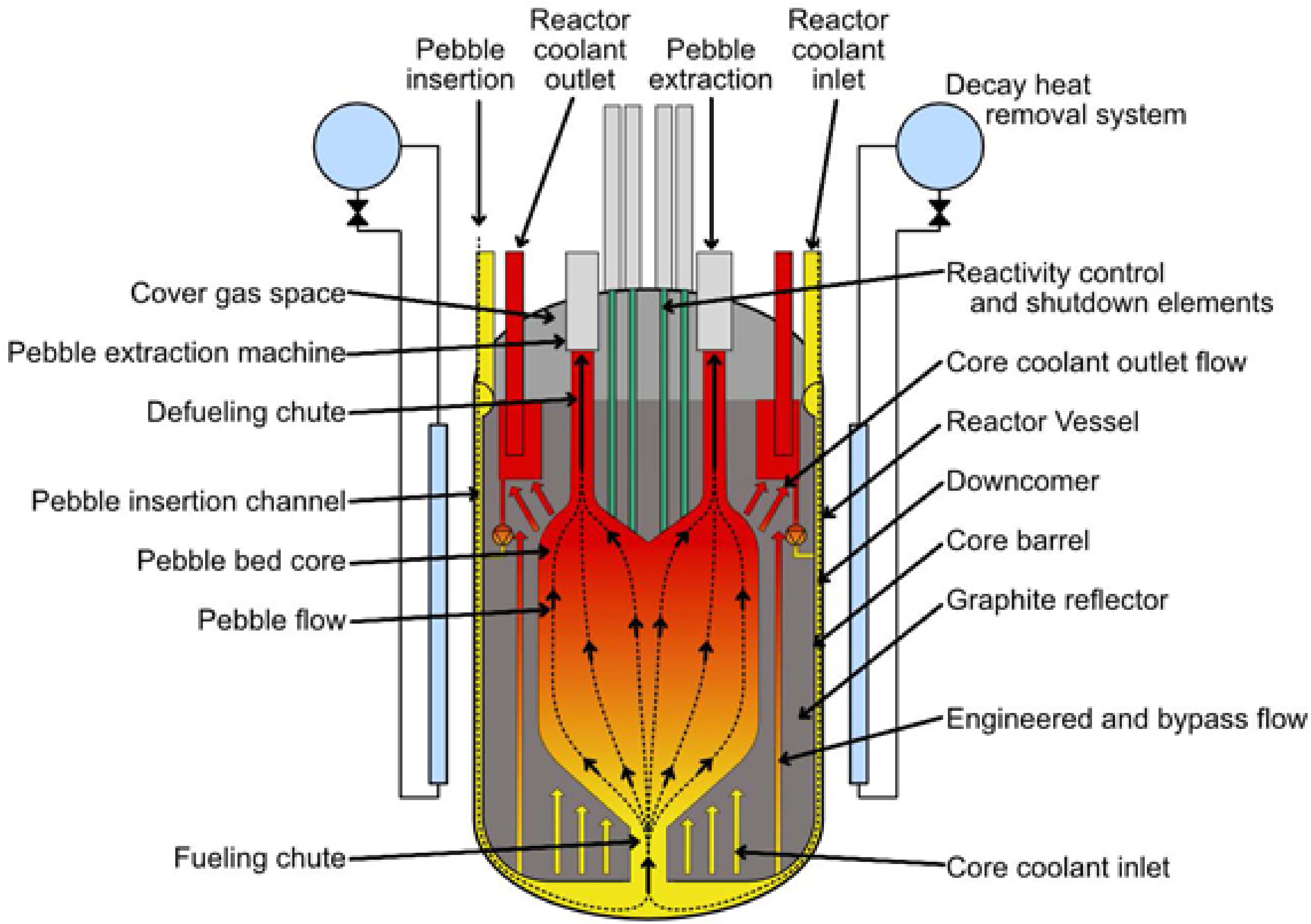


# New fuel form - TRISO

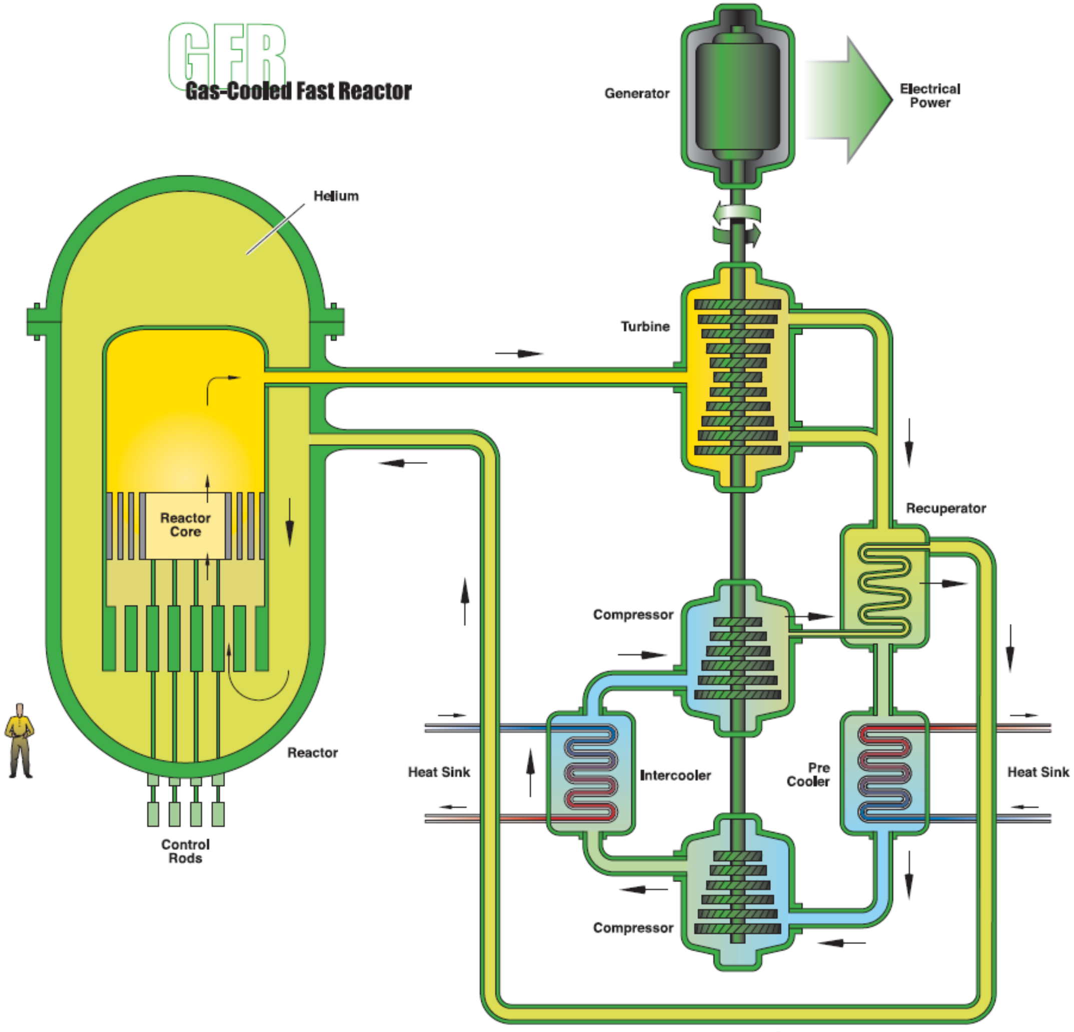


# Fluoride-salt High-temperature Reactor (FHR)



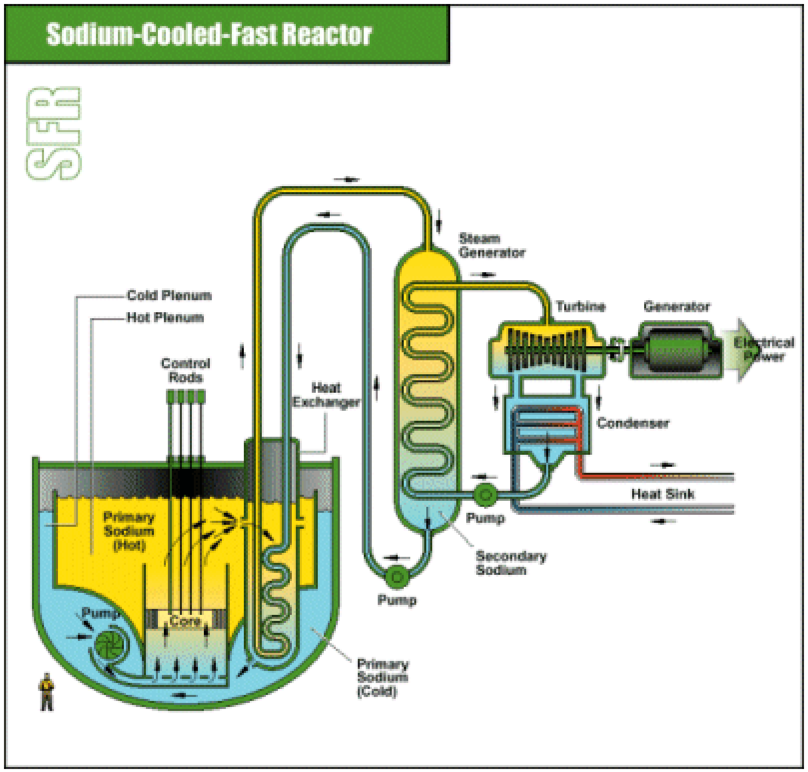


# Gas-cooled Fast Reactor



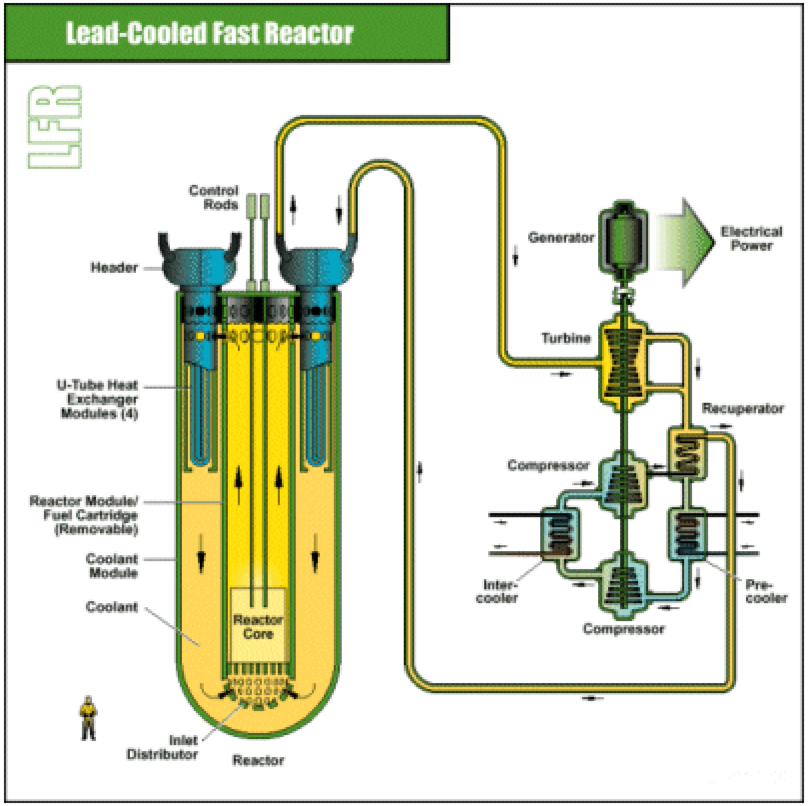

- He cooled with direct Brayton cycle for high efficiency
- Closed fuel cycle
- Low Power Density
- Fuel Rods, $^{239}Pu$

# 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), $^{239}Pu$

# 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?

# 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.